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LABORATORY EXPERIMENTS TO MEASURE THE EFFECTS OF SIGNAL BANDWID--ETC(U)
JUN 67   P H HAWKES

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(6) LABORATORY EXPERIMENTS TO MEASURE THE EFFECTS OF SIGNAL BANDWIDTH AND SYSTEM SAMPLE RATE ON PROCESSING GAIN.[redacted]

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FORWARD

This Technical Memorandum reports the results of processing gain experiments which have been conducted in the laboratory by P. Hawkes and J. Ehlers of Code 3150D, under SF 101 03 16, Task 11197 (NEL E119). The results reported here represent only a small portion of the planned experimental program, but the results are believed to be of enough general interest to others at NEL to warrant early publication in this informal manner. ~~Only limited distribution outside of the laboratory is anticipated.~~

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LIST OF ILLUSTRATIONS

BACKGROUND

Code 3150D is conducting a program of laboratory sonar signal processing experiments which is intended to serve several purposes. Among them are (1) the evaluation, under laboratory conditions, of a processing system similar to the LORAD system[1] which has been used for experiments at sea for a number of years, (2) technical support for the laboratory's growing efforts in Project Office work, and (3) the investigation of problems of more general interest in the field of signal processing.

The experimental program began with a study of doppler spreading[2] and continued with processing gain experiments, which are reported in this technical memorandum. Additional experiments are planned for the future and will be reported as results become available.

A REVIEW OF THE SYSTEM

This memorandum describes a series of processing gain measurements which have been conducted with a laboratory signal processing system[3,4,5]. The cited references describe the system in detail, but a general description will be given here for the reader's convenience.

The basic signal processor is a multiplex DELTIC clipper-correlator. Recent modifications allow the selection of input signal sample rates of 200 Hz (the original rate), 400 Hz, or 800 Hz. The modifications have been achieved by reducing the number of input channels to one signal channel and one reference channel.

Input to the DELTIC correlator is provided by an auxiliary unit which contains a pseudonoise generator (PNG) and sets of three bandpass filters. Only one set

of filters was used in this experiment. The three filters of this set have a center frequency (f_o) of 1500 Hz and bandwidths (B) of 100 Hz, 30 Hz, and 10 Hz. Externally generated signals can also be supplied to the DELTIC correlator through the auxiliary unit.

Other functions of the auxiliary unit are to control the system timing and to provide the necessary interfacing between the system output and a USQ-20 general purpose computer.

A recent addition to the system is a "PNG Decoder". The decoder can generate a pulse which is coincident in time with a pseudonoise-signal output "correlation spike". The pulse sets a bit in the computer input word indicating the presence of a "signal". The decoder can, with some modifications, perform a similar function with other signal types.

Another significant system modification concerns the comb filter at the output of the correlator. Originally, all of the 34 comb filter teeth were applied to the input of a "greatest of" OR circuit followed by an envelope detector. It is now possible to bypass the OR circuit and to measure the envelope detected output of any one of the 34 individual teeth.

A DISCUSSION OF PROCESSING GAIN

The purpose of this section is to define "processing gain" and to discuss its measurement in the laboratory

The basic definition of processing gain is deceptively simple:

$$P.G. \equiv \frac{\left(\frac{S}{N}\right)_{out}}{\left(\frac{S}{N}\right)_{in}} \qquad (1)$$

where $(S/N)_{out}$ = processor output signal-to-noise power ratio

and $(S/N)_{in}$ = processor input signal-to-noise power ratio

Technical literature seems to be in universal agreement that $(S/N)_{in}$ is the rms signal power divided by rms noise power. There is considerably less agreement on how $(S/N)_{out}$ should be defined. Three common definitions are given below:

a) $(S/N)_{out}$ = rms signal power divided by rms noise power

b) $(S/N)_{out}$ = peak signal power divided by rms noise power

c) $(S/N)_{out}$ = peak signal power minus average noise power divided by rms noise power measured about the mean noise level.

Definitions b) and c) will be used in this memorandum to define "Processing Gain I" and "Processing Gain II", respectively.

Processing Gain I is the conventional definition used in most theoretical work. It is a standard against which any measured processing gain can be compared. An equation for it can be derived from signal and noise energy considerations alone.

$$(P.G.\ I)_{MAX} = 2B \cdot T$$

where B = signal bandwidth (Hz)

and T = signal duration (sec)

The derivation is general and is independent of the processor implementation. However, it is conventional to consider the maximum theoretical processing gain of a difference frequency correlator to be half of the above value. This is because a difference frequency correlator is carrier phase insensitive, causing a 3 dB reduction in processing gain. Therefore, the convention of using

$$(P.G.\ I)_{MAX} = B \cdot T \tag{2}$$

will be followed in this memorandum.

In the case of the laboratory processor, the $(S/N)_{out}$ for determining P.G. I directly would have to be measured at the comb filter output before envelope detection, but the output is not available at that point. All measurements must necessarily be made on the envelope detected output. It is for this reason that the definition of P.G. II is useful. P.G. II may be calculated from measurements made on the available output. The output measurements required are (1) peak signal (S_p); (2) mean or average noise level (μ_N); and (3) standard deviation of noise (σ_N). If all measurements are made in volts, then

$$P.G.\ II = 20 \log \left(\frac{S_p - \mu_N}{\sigma_N} \right)_{out} - 20 \log \left(\frac{S_{RMS}}{N_{RMS}} \right) \text{ in dB} \tag{3}$$

P.G. I may be calculated from the same set of measurements if certain assumptions are made about the envelope detector and the output noise statistics. The input signal-to-noise ratio is identical for both definitions of processing gain. The peak output signal is also the same if a perfect envelope detector is assumed. The difference between the two definitions of processing gain becomes apparent when output noise is considered. If it is assumed that the undetected output noise is described by a Gaussian probability density function, then,

$$p(V_G) = \frac{1}{\sqrt{2\pi}\,\sigma_G} \epsilon^{-\frac{1}{2}\left(\frac{V_G}{\sigma_G}\right)^2} \tag{4}$$

where V_G = instantaneous noise voltage

and σ_G = rms noise voltage

Perfect envelope detection of Gaussian noise results in Rayleigh distributed noise, described by

$$p(V_R) = \frac{V_R}{N} \epsilon^{-\left(\frac{V_R^2}{2N}\right)} \tag{5}$$

where V_R = instantaneous noise voltage

and $N = \sigma_G^2$ = noise power of original Gaussian distribution.

The average value of a Rayleigh distribution may be shown to be:

$$\mu_R = \sqrt{\frac{\pi}{2} N} = \sqrt{\frac{\pi}{2}}\, \sigma_G$$

so that

$$\sigma_G = \sqrt{\frac{2}{\pi}}\, \mu_R = 0.8\ \mu_R \tag{6}$$

An expression similar to equation (3) can now be written for Processing Gain I:

$$\text{P.G. I} = 20 \log \left(\frac{S_p}{0.8\, \mu_R}\right)_{out} - 20 \log \left(\frac{S_{RMS}}{N_{RMS}}\right)_{in} \text{ in dB} \tag{7}$$

A comparison of equations (3) and (7) will show that Processing Gain II is 3.7 dB higher than Processing Gain I for high output (and input) signal-to-noise ratios. The two measures of processing gain are equal when $S_p = 1.74\, \mu_N$ (low signal-to-noise ratio).

SOME PRELIMINARY PROBLEMS

During the checkout of the laboratory processing equipment and later when a setup was being prepared for the processing gain experiments, two peculiarities were noticed in the processor output signal.

The first was the presence of "super" correlation spikes as illustrated in Figures 1a and 1b. The photographs show a series of processor correlation spikes produced from the zero doppler comb filter tooth (tooth #17). The input signal in both cases was a noise-free PN signal having a 100 Hz bandwidth. The sample rate was 200 Hz in Figure 1a and 800 Hz in Figure 1b. The consistent amplitudes seen in Figure 1b are due to the high ratio of sampling frequency to signal bandwidth.[6] The amplitudes in Figure 1a are much less consistent, as expected.

The surprising features of the photographs are the three "super" correlation spikes in Figure 1a having amplitudes exceeding any of those in Figure 1b. The random occurance of these "super" spikes was always observed at the 200 Hz sample rate but was never observed at the 400 Hz or 800 Hz sample rates.

The second peculiarity, doppler ambiguity with the 200 Hz sample rate, is discussed in reference 2. This second peculiarity was discovered while investigating the first one. The investigation involved replacing the DELTIC correlator's own heterodyne oscillators with a frequency synthesizer which is capable of generating a precise, stable, but variable frequency. It was then possible to vary the heterodyne difference frequency, defined by

$$\Delta f_H = f_{SIG} - f_{REF} \tag{8}$$

where f_{SIG} = signal heterodyne frequency

and f_{REF} = reference heterodyne frequency

It was found that when Δf_H was varied to approximate a doppler shift, two simultaneous correlation spikes were produced from two comb filter teeth located symmetrically about tooth #17. When no doppler shift was inserted, "super" spikes were observed as described above.

An explanation of these peculiarities was given by E. C. Westerfield and M. K. Brandon, Code 3195. Their explanation considers the sampling process which takes place in the system. Sampling the signal and reference inputs generates replicas of their original spectra at periodic intervals corresponding to the sample rate. The signal and reference inputs originally differed by an amount Δf_H due to heterodyning, so that after sampling, the series of replicas then differ, one from the other, by the same Δf_H. The correlation process heterodynes one series against the other, generating all possible sum and difference frequencies. In the special case when the sampling frequency is exactly $2\Delta f_H$, the difference frequencies combine into a single line whose amplitude depends on the relative phase of the signal and reference samples. When the sampling frequency is slightly different from $2\Delta f_H$, two closely spaced spectral lines are produced. This is the case when the sampling frequency is 200 Hz and Δf_H = 100 Hz. The other two sample frequencies generate widely spaced lines only one of which ever appears at the output of the comb filter.

A true measure of processing gain can be obtained only when "super" correlation spikes are avoided. This was done by increasing Δf_H slightly by means of the frequency synthesizer. All measurements were therefore taken from comb filter tooth #18.

THE EXPERIMENT

These experiments were designed to measure processing gain with ideal (undistorted) input signals. Data was taken to measure processing gain as a function of signal bandwidth, signal sampling rate, and input signal-to-noise ratio. A comparison of signal types (PN vs. FM) was also planned, but the procurement of a satisfactory FM signal generator has delayed such a comparison.

Setup

Figure 2 shows the setup used to supply the various DELTIC correlator inputs. Also shown is the PNG decoder and its relationship to the generation of the "Transmit" control signal and setting of the "Correlation Indicator" bit.

The 15 stage PNG supplied the input signal which was added to noise in the summing operational amplifier. The signal plus noise was then bandpass filtered and applied to the signal and reference DELTICs through a single buffer amplifier. This arrangement of adding signal and noise required only one bandpass filter for each bandwidth, assuring that the signal and reference inputs were identical.

The other DELTIC correlator inputs are shown being supplied by the frequency synthesizer which replaces both the signal and reference heterodyne oscillators. The reason for the replacement has been discussed in an earlier section of this memorandum.

Procedure

An explanation of the experiment can best be given by means of the following outline. The outline describes the experimental procedure which was followed in taking data.

1. Select desired sample rate and signal bandwidth.
2. Load reference DELTIC with a noise-free input.
    a. Set signal attenuator to zero and noise attenuator to maximum (100 dB).
    b. Set frequency synthesizer to 1450.00 Hz (reference heterodyne frequency).
    c. Push the TRANSMIT button. (The Transmit mode is enabled for a period of time determined by the PNG decoder. At the end of that time, the Receive mode is automatically enabled.)

3. Measure input signal-to-noise ratio.

a. With signal and noise still set as in step 2a, measure the input signal with a voltmeter or with the computer. (More will be said about the computer measurements later.)

b. Repeat the measurement with the noise attenuator set to zero and the signal attenuator set to maximum.

c. Calculate the maximum input signal-to-noise ratio from steps 3a and 3b. (Nominally 15 dB)

4. Measure output noise.

a. Set frequency synthesizer to 1550.10 Hz (signal heterodyne frequency).

At this point in the test procedure, the DELTIC correlator is operating in the Receive mode, the reference input has been loaded and the signal heterodyne frequency is being applied. All that remains to be done before commencing processing is to measure output noise and then to apply input signal.

b. Measure envelope detected output noise from comb filter tooth #18 using the computer.

5. Measure output signal.

a. Set signal attenuator to zero. The DELTIC correlator now has signal plus noise applied. Periodic correlation spikes will be produced at the PNG recycle rate, which is once every 8.192 seconds.

b. Measure output signal with the computer.

c. Reduce the signal input by 2 dB and again measure the output signal. Repeat this step until the output signal approaches the noise level.

Following the above procedure results in data for a plot of Processing Gain vs. Input Signal-to-Noise Ratio for a given sample rate and bandwidth. Data

for other sample rate/bandwidth combinations is obtained by repeating the procedure for each additional combination. All possible combinations of the three sample rates (200, 400, and 800 Hz) and the three internal bandpass filters (10, 30, and 100 Hz) were processed. In addition, a 350 Hz bandwidth signal was sampled at 800 Hz, yielding a total of ten combinations.

Computer Processing

The computer input consists of 30-bit data words which are generated at the system sample rate. Twelve bits of the data word represent the amplitude of the input to an analog-to-digital converter. One bit identifies the presence (or absence) of a signal correlation spike. Sixteen bits are counter information. The computer used this information for three calculations in the test procedure; (1) input signal-to-noise ratio, (2) output noise, and (3) output signal. One computer subroutine makes the calculations for the first two cases while another subroutine is required for the third calculation.

The first subroutine calculates and prints out the mean (μ) and standard deviation (σ) of the amplitudes of 10,000 consecutive input words. The subroutine also sorts the words in each bin to provide histogram data. Figure 3 illustrates the output format of this subroutine. The items in the heading refer to "Noise Out", but they apply equally to the input signal and input noise. The items are self-explanatory with the possible exception of "Noise Out, Equivalent RMS." This is simply 0.8μ and has meaning only for the output measurements. It represents the rms output noise which is used in calculating Processing Gain I. The meaning of the histogram tabulations is as follows:

$$X = \text{bin number}$$

$$H(X) = \frac{N_X}{N\Delta X} = \text{probability density} \qquad (9)$$

where N_X = number of words in bin X

N = total number of words (10,000)

ΔX = bin size (2^{-7} x 10 volts)

$$P(X) = \sum_{X=0}^{X} H(X) = \text{cumulative probability} \quad (10)$$

Input signal and noise were measured with the computer by disconnecting the normal input (comb filter output) to the system analog-to-digital converter and applying the output of the variable gain operational amplifier (Figure 2). Measurements made in this way eliminate the tedious and inaccurate job of making voltmeter measurements of noise or pseudonoise inputs.

The computer subroutine which was used to measure the output signal simply scanned all of the computer input words searching for one having its correlation indicator bit set. When one was found it was called an Indicator Word. The peak correlation spike was then known to be present a certain number of words later. This delay, caused by the processor, is a function of the sample rate as shown below.

Sample Rate	Delay
200 Hz	3 words ± 1 word
400 Hz	6 words ± 1 word
800 Hz	12 words ± 1 word

The one word uncertainty in the delay is caused by the asynchronous operation of the PNG and the DELTIC correlator.

A print-out (Figure 4) of signal amplitudes is initiated automatically after 50 correlation spikes have been recorded. The print-out lists the Indicator

Word and five consecutive words which bracket the known location of the peak correlation spike. The amplitudes of the three inner words (words 1, 2 and 3) are examined by the computer and the decimal value, in volts, of the highest of the three is printed in the Maximum Amplitude Column. Five words, rather than three, are printed so that the data can be checked at a later time to see that the peak signal does occur in one of the three inner words.

The test conditions are summarized at the bottom of the print-out. Maximum Amplitude is the highest of the 50 individual peak correlation spikes. Average Amplitude and Standard Deviation are self-explanatory. Output S/N is the Average Amplitude divided by 0.8 , measured in dB. Average Processing Gain is the difference (in dB) between Output S/N and Input S/N. It is the value of Processing Gain I. Processing Gain II was calculated manually from the data.

RESULTS

Curves of Processing Gain I and II are shown in Figures 5 through 17. The curves for each definition of processing gain are presented in two ways for ease of comparison. First, the sample rate is kept constant while the signal bandwidth is made a parameter, then signal bandwidth is kept constant while sample rate is made a parameter. The 350 Hz bandwidth signal was sampled only at 800 Hz, so a separate curve was plotted for that data.

Using T = 4.7 seconds, equation (2) gives a maximum Processing Gain I of 470 (26.7 dB), 141 (21.5 dB), and 47 (16.7 dB) for the 100 Hz, 30 Hz, and 10 Hz signal bandwidths respectively, independent of sample rate. Figure 5 shows the measured processing gains to be 28 dB, 25.6 dB, and 22.1 dB respectively, apparently somewhat more than is theoretically possible. The definition of signal bandwidth is the most probable cause of the high processing gain values.

The bandwidth of a filter is conventionally measured at the -3 dB points. This is satisfactory for most analog work, but it can be misleading when dealing with a nonlinear (clipped) system such as the DELTIC correlator. The measured processing gains are the theoretical values which would result from filters having bandwidths of 134 Hz, 76 Hz, and 37 Hz. Figures 18, 19, and 20 show the bandpass characteristics of the laboratory processor's three internal filters. The curves show that the 100 Hz filter is 134 Hz wide at 15 dB attenuation, the 30 Hz filter is 76 Hz wide at 25 dB attenuation, and the 10 Hz filter is 37 Hz wide at 18 dB attenuation. It therefore does not seem unreasonable to consider the filter bandwidths to be determined at the -20 dB points rather than at the more conventional -3 dB points.

Another possible cause of the excessive processing gain is the method of measuring "output noise" for Processing Gain I. The noise could not be measured directly (before envelope detection). Envelope detected noise was therefore measured and an 0.8μ conversion factor was used (equation (6)). The conversion factor assumes the output noise to have a Rayleigh distribution after detection. However, this is not exactly true. An indication of how true it is is given in Figure 22 where the measured output noise distribution and a Rayleigh distribution having the same mean and standard deviation are plotted. The two curves are slightly different, causing the conversion factor to be slightly in error. The error would affect only the absolute value of processing gain and would have no effect on the relative values, allowing valid comparisons to be made. The Processing Gain II data was measured directly so that no conversion errors exist.

A comparison of the processing gain curves gives further evidence that the 3 dB definition of filter bandwidth is misleading. Figure 5 shows approximately

a 3 dB difference in processing gain between each successive bandwidth, rather than the expected 5 dB. The sample rate of 800 Hz is more than adequate (in theory) to preserve the signal identity, so that the differences in processing gain must be due solely to signal bandwidth. The 3 dB difference in the adjacent processing gain curves indicates a 4:2:1 ratio of signal bandwidth. This is the case when the bandpass filter characteristics are measured at the 20 dB points.

Figure 8 shows the variation in Processing Gain I of a 100 Hz bandwidth signal as a function of sample rate. An increase of 1 or 2 dB results when the sample rate is doubled from 400 Hz to 800 Hz. About 0.5 dB of this increase can be attributed to improved sampling of the correlation function.[6] The remainder must be due to inadequate signal sampling at the 400 Hz rate, indicating that the "100 Hz bandwidth" signal is actually a wider band signal.

Figures 8, 9, and 10 show that the 200 Hz sample rate results in a loss of from 2 to 4 dB at all bandwidths when compared to the results achieved with the 400 Hz rate. This is due primarily to the division of the output correlation spike between two comb filter teeth.

The two processing gain curves of the 350 Hz bandwidth signal sampled at 800 Hz are shown in Figure 17. The Maximum Processing Gain I is far below the theoretical value of 32.2 dB. Most of this loss is due to an inadequate sample rate. Figure 21 shows the 350 Hz filter characteristic. The bandwidth is seen to be 700 Hz at 20 dB. This wide bandwidth would require a sample rate which is far above the present equipment's capability.

Another possible source of correlation loss in the present system is the location of the signal band after heterodyning. The signal is heterodyned down

to a band centered on 50 Hz. The "100 Hz bandwidth" signal must suffer some distortion due to zero frequency crossover because the bandwidth is actually greater than ± 50 Hz. Also, all odd harmonics which are generated by the clipping process overlap in the 100 Hz bandwidth case causing additional signal distortion.

CONCLUSIONS

Most of the conclusions of this memorandum have been stated in previous sections, but a brief summary will be inserted here;

(1) The combination of a 100 Hz difference frequency and a 200 Hz sample rate was an unfortunate choice for the original DELTIC correlator. In general, a condition to be avoided is $f_s = 2 f_H$ where f_s is the system sample frequency and f_H is the heterodyne difference frequency,

(2) The convention of measuring filter bandwidths at the -3 dB points is misleading in a nonlinear system. Selecting the -20 dB points seems to be a better measure of filter bandwidth,

(3) Care should be used when assessing statements concerning processing gain because the definition (or at least the measurement) of processing gain is ambiguous. The two definitions which are used in this memorandum result in a measured difference of 1 dB in favor of Processing Gain II, and

(4) The processor's envelope detected output noise does not follow a Rayleigh distribution. The actual distribution is biased toward the lower noise values.

THE FUTURE

Several interesting problems remain to be investigated when time and equipment permit. Of primary interest is the comparison of PN and FM signal types. This comparison should permit verification (or rejection) of the theory concerning the definition of filter bandwidth because an FM signal has a near-ideal wide-band frequency spectrum.

An investigation should also be carried out to determine the advantage of heterodyning to a frequency band which is displaced from zero. Preliminary experiments indicate that the output noise level drops by 1 or 2 dB when the heterodyned 100 Hz signal band is shifted upward by 50 Hz.

Another interesting possibility is the total elimination of heterodyning to some lower frequency. Either the signal or reference input must be heterodyned with a 100 Hz oscillator to generate the proper system difference frequency, but direct sampling of these frequencies may be possible.

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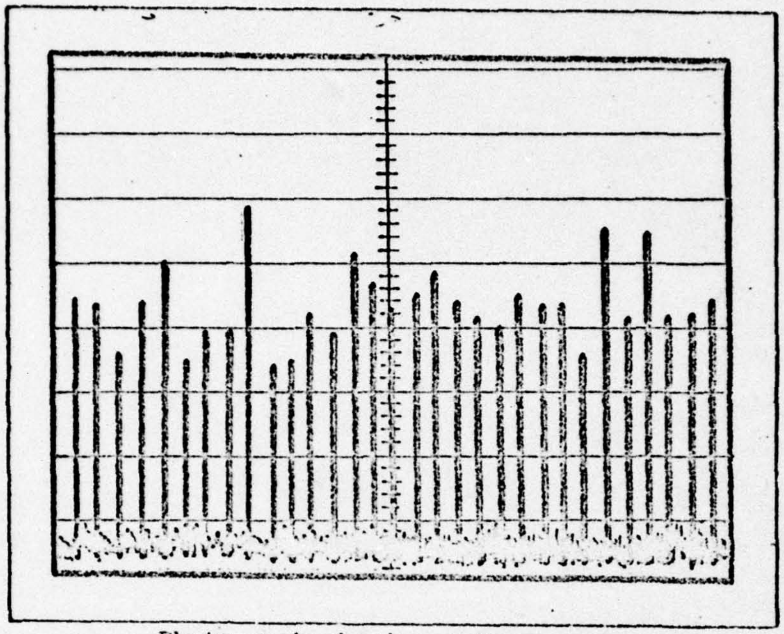
4. NEL Technical Memorandum 846, Laboratory Instrumentation for Sonar Signal Parameter Studies, by P. Hawkes, 17 Sept 1965

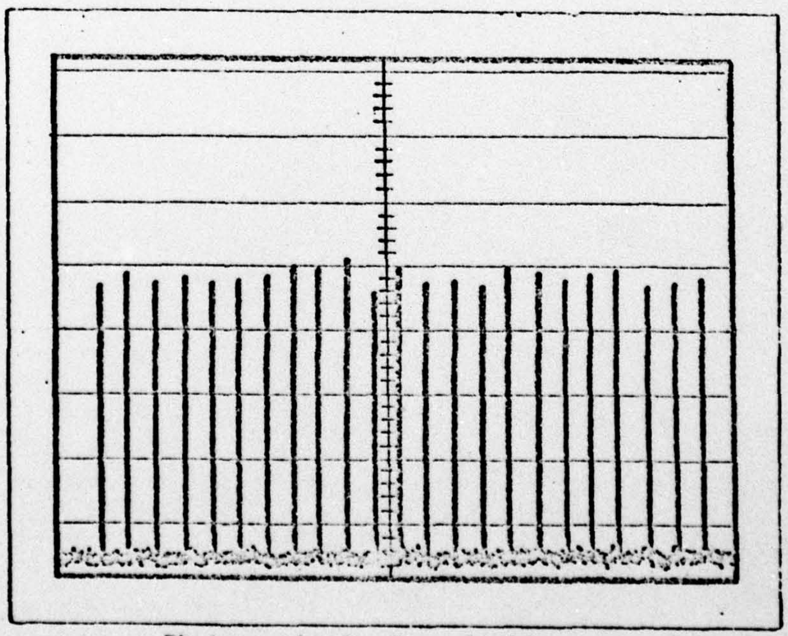
5. Instruction Manual for a Multiplex DELTIC Correlator, Computer Control Co., NEL Contract N123(953)21698A

6. NEL Report 1299, Pseudorandum Signal Correlation in Sonar Systems, by W. B. Allen, 24 June 1965



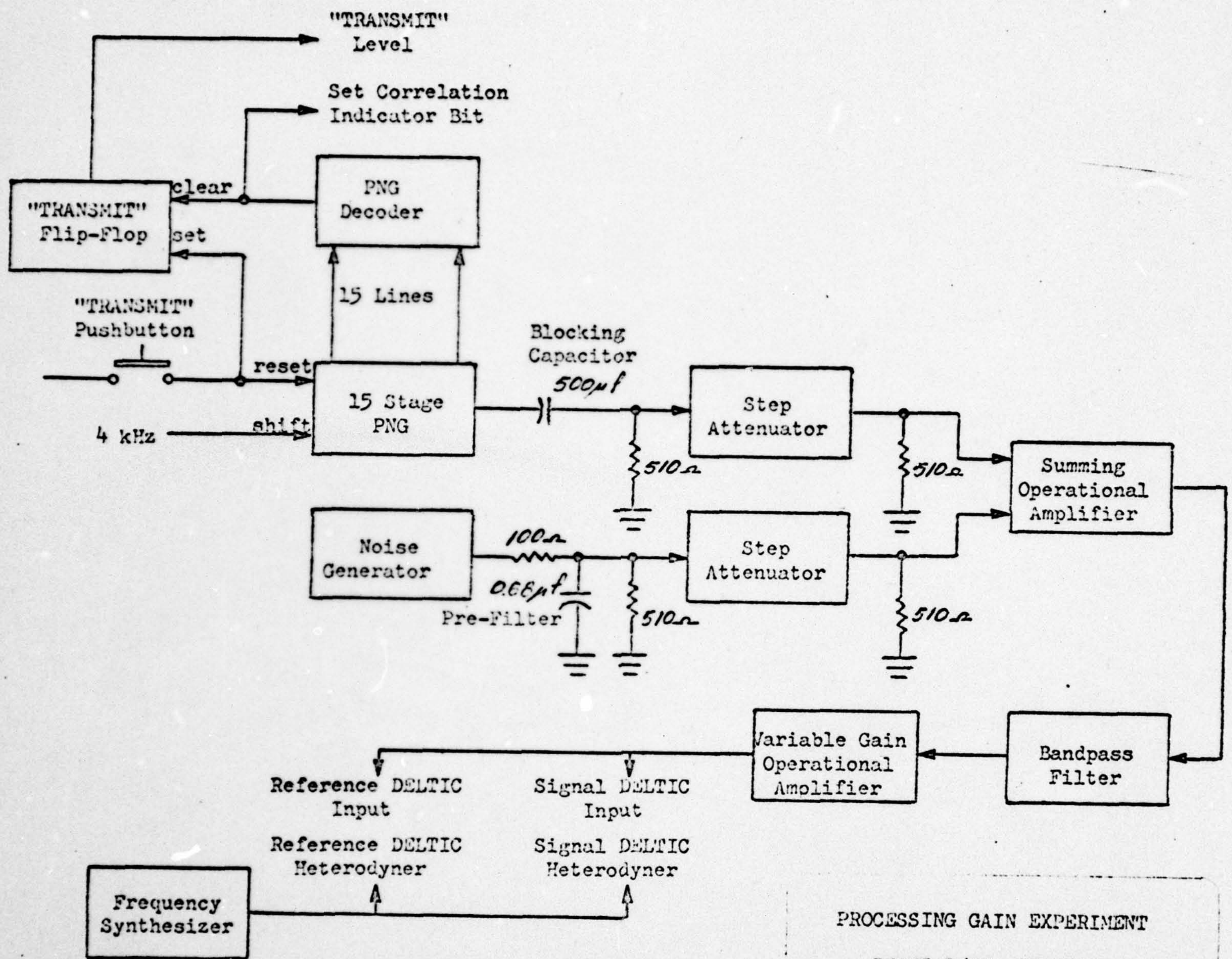
Photograph showing extreme amplitude variation of correlation spikes with B=100 Hz, f_s=200 Hz.

Figure 1a



Photograph showing slight amplitude variation of correlation spikes with B=100 Hz, f_s=800 Hz.

Figure 1b



PROCESSING GAIN EXPERIMENT

INPUT BLOCK DIAGRAM

Figure 2

PROCESSING GAIN EXPERIMENT
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SAMPLE RATE = 800 CPS
BANDWIDTH = 100 CPS
SIGNAL TYPE = PN

NOISE OUT, AVERAGE PEAK = 0.41778
NOISE OUT, STD. DEVIATION = 0.25314
NOISE OUT, EQUIVALENT RMS = 0.33422

X	H(X)	P(X)	X	H(X)	P(X)
0	0.1535	0.1535	25	0.0000	127.9687
1	15.7529	15.9064	26	0.0000	127.9687
2	18.6450	34.5515	27	0.0000	127.9687
3	16.8790	51.4306	28	0.0000	127.9687
4	16.7127	68.1433	29	0.0000	127.9687
5	13.7822	81.9255	30	0.0000	127.9687
6	11.5043	93.4299	31	0.0000	127.9687
7	9.1881	102.6181	32	0.0000	127.9687
8	7.5501	110.1682	33	0.0000	127.9687
9	5.1827	115.3510	34	0.0000	127.9687
10	4.0310	119.3820	35	0.0000	127.9687
11	2.9432	122.3253	36	0.0000	127.9687
12	2.1498	124.4751	37	0.0000	127.9687
13	1.3308	125.8060	38	0.0000	127.9687
14	0.9213	126.7274	39	0.0000	127.9687
15	0.4222	127.1497	40	0.0000	127.9687
16	0.2815	127.4312	41	0.0000	127.9687
17	0.2303	127.6616	42	0.0000	127.9687
18	0.1663	127.8279	43	0.0000	127.9687
19	0.0511	127.8791	44	0.0000	127.9687
20	0.0511	127.9303	45	0.0000	127.9687
21	0.0127	127.9431	46	0.0000	127.9687
22	0.0127	127.9559	47	0.0000	127.9687
23	0.0127	127.9687	48	0.0000	127.9687
24	0.0000	127.9687	49	0.0000	127.9687

Note: Data not normalized

Example of computer print-out of input and output statistics.

Figure 3

PROCESSING GAIN EXPERIMENT
NOV 23 66

NO.	INDICATOR WORD			LOWER WORD			WORD 1			WORD 2			WORD 3			HIGHER WORD			MAX AMP
	AMP	R	COUNTER	AMP	R	COUNTER	AMP	R	COUNTER	AMP	R	COUNTER	AMP	R	COUNTER	AMP	R	COUNTER	
1	112	1	152635	5514	0	152647	6600	0	152650	7022	0	152651	6704	0	152652	6261	0	152653	8.796
2	212	1	167110	5164	0	167122	6204	0	167123	7201	0	167124	7100	0	167125	6431	0	167126	9.067
3	204	1	3354	5274	0	3366	6270	0	3367	7102	0	3370	7216	0	3371	6356	0	3372	9.098
4	641	1	17625	5630	0	17637	6355	0	17640	6574	0	17641	6634	0	17642	6346	0	17643	8.507
5	300	1	34116	5434	0	34130	6270	0	34131	6652	0	34132	7212	0	34133	6740	0	34134	9.089
6	352	1	50370	5610	0	50402	6564	0	50403	6724	0	50404	6526	0	50405	5424	0	50406	8.644
7	131	1	64633	5470	0	64645	6424	0	64646	7276	0	64647	6656	0	64650	6026	0	64651	9.216
8	440	1	101075	5324	0	101107	6332	0	101110	6721	0	101111	6572	0	101112	6306	0	101113	8.637
9	64	1	115355	5346	0	115367	6140	0	115370	6664	0	115371	7035	0	115372	6440	0	115373	8.822
10	240	1	131614	5662	0	131626	6440	0	131627	6760	0	131630	6770	0	131631	6475	0	131632	8.732
11	220	1	146073	4721	0	146105	6343	0	146106	7134	0	146107	7240	0	146110	6360	0	146111	9.142
12	206	1	162355	5401	0	162367	6440	0	162370	7230	0	162371	7334	0	162372	6624	0	162373	9.289
13	311	1	176615	5404	0	176627	6355	0	176630	7260	0	176631	7114	0	176632	6360	0	176633	9.181
14	121	1	13116	5334	0	13130	6364	0	13131	7061	0	13132	6672	0	13133	6034	0	13134	8.871
15	51	1	27373	5300	0	27405	6162	0	27406	7024	0	27407	7073	0	27410	6424	0	27411	8.896
16	46	1	43633	5602	0	43645	6630	0	43646	7152	0	43647	7004	0	43650	6543	0	43651	9.011
17	220	1	60115	5552	0	60127	6302	0	60130	6604	0	60131	6636	0	60132	6514	0	60133	8.512
18	151	1	74373	5636	0	74405	6534	0	74406	6720	0	74407	7224	0	74410	6500	0	74411	9.113
19	150	1	110624	5300	0	110636	6271	0	110637	6536	0	110640	6730	0	110641	6334	0	110642	8.654
20	54	1	125075	5500	0	125107	6366	0	125110	6760	0	125111	6566	0	125112	6014	0	125113	8.713
21	100	1	141331	4701	0	141343	5720	0	141344	6704	0	141345	7142	0	141346	6514	0	141347	8.991
22	50	1	155571	5614	0	155603	6354	0	155604	6730	0	155605	6725	0	155606	6315	0	155607	8.654
23	774	1	172064	5621	0	172076	6423	0	172077	7200	0	172100	7200	0	172101	6220	0	172102	9.064
24	160	1	6327	5350	0	6341	6272	0	6342	7072	0	6343	7060	0	6344	6334	0	6345	8.893
25	51	1	22616	6000	0	22630	6361	0	22631	7031	0	22632	6651	0	22633	6420	0	22634	8.813
26	325	1	37075	5240	0	37107	6434	0	37110	7136	0	37111	6714	0	37112	5760	0	37113	8.981
27	275	1	53365	5234	0	53377	6311	0	53400	7026	0	53401	6765	0	53402	6372	0	53403	8.805
28	443	1	67625	5462	0	67637	6544	0	67640	7206	0	67641	7210	0	67642	6364	0	67643	9.084
29	215	1	104075	5234	0	104107	6112	0	104110	6720	0	104111	6751	0	104112	6226	0	104113	8.695
30	114	1	120355	5320	0	120367	6200	0	120370	6634	0	120371	6750	0	120372	6105	0	120373	8.693
31	141	1	134615	5614	0	134627	6650	0	134630	7010	0	134631	6614	0	134632	6332	0	134633	8.771
32	310	1	151063	5151	0	151075	6240	0	151076	7106	0	151077	7111	0	151100	6362	0	151101	8.930
33	210	1	165324	5730	0	165336	6406	0	165337	7025	0	165340	7034	0	165341	6542	0	165342	8.820
34	200	1	1555	5510	0	1567	6474	0	1570	7141	0	1571	6626	0	1572	6022	0	1573	8.989
35	231	1	16067	5314	0	16101	6060	0	16102	7006	0	16103	7120	0	16104	6372	0	16105	8.947
36	266	1	32365	5721	0	32377	6602	0	32400	7050	0	32401	7211	0	32402	6271	0	32403	9.086
37	66	1	46633	5621	0	46645	6460	0	46646	6700	0	46647	6714	0	46650	6532	0	46651	8.625
38	420	1	63115	5446	0	63127	6172	0	63130	6670	0	63131	7251	0	63132	6470	0	63133	9.164
39	105	1	77370	5344	0	77402	6063	0	77403	6564	0	77404	6700	0	77405	6432	0	77406	8.595
40	70	1	113634	5120	0	113646	6014	0	113647	6641	0	113650	6502	0	113651	6330	0	113652	8.520
41	200	1	130113	5266	0	130125	6426	0	130126	7220	0	130127	6770	0	130130	6540	0	130131	9.103
42	262	1	144364	5510	0	144376	6370	0	144377	7114	0	144400	7131	0	144401	6343	0	144402	8.969
43	326	1	160624	5524	0	160636	6446	0	160637	7016	0	160640	6470	0	160641	6151	0	160642	8.786
44	203	1	175071	5410	0	175103	6372	0	175104	7000	0	175105	6725	0	175106	5735	0	175107	8.752
45	214	1	11322	5420	0	11334	6430	0	11335	6670	0	11336	6701	0	11337	6506	0	11340	8.598
46	321	1	25571	5442	0	25603	6235	0	25604	6660	0	25605	6554	0	25606	6156	0	25607	8.556
47	66	1	42071	5710	0	42103	6224	0	42104	6752	0	42105	6422	0	42106	6200	0	42107	8.698
48	330	1	56365	5630	0	56377	6432	0	56400	6570	0	56401	6752	0	56402	6440	0	56403	8.698
49	353	1	72634	5070	0	72646	6074	0	72647	7000	0	72650	7022	0	72651	6240	0	72652	8.796
50	104	1	107110	5370	0	107122	6471	0	107123	7013	0	107124	6645	0	107125	5645	0	107126	8.779

SAMPLE RATE= 800 CPS
BANDWIDTH = 100 CPS
SIGNAL TYPE= PN

MAX AMP. = 9.289
AVG AMP. = 8.857
STN DEV. = 0.206

INPUT S/N = 13.0 DB
OUTPUT S/N= 25.8 DB
AVERAGE PG= 12.8 DB

Example of computer print-out of
output signal amplitudes.

Figure 4

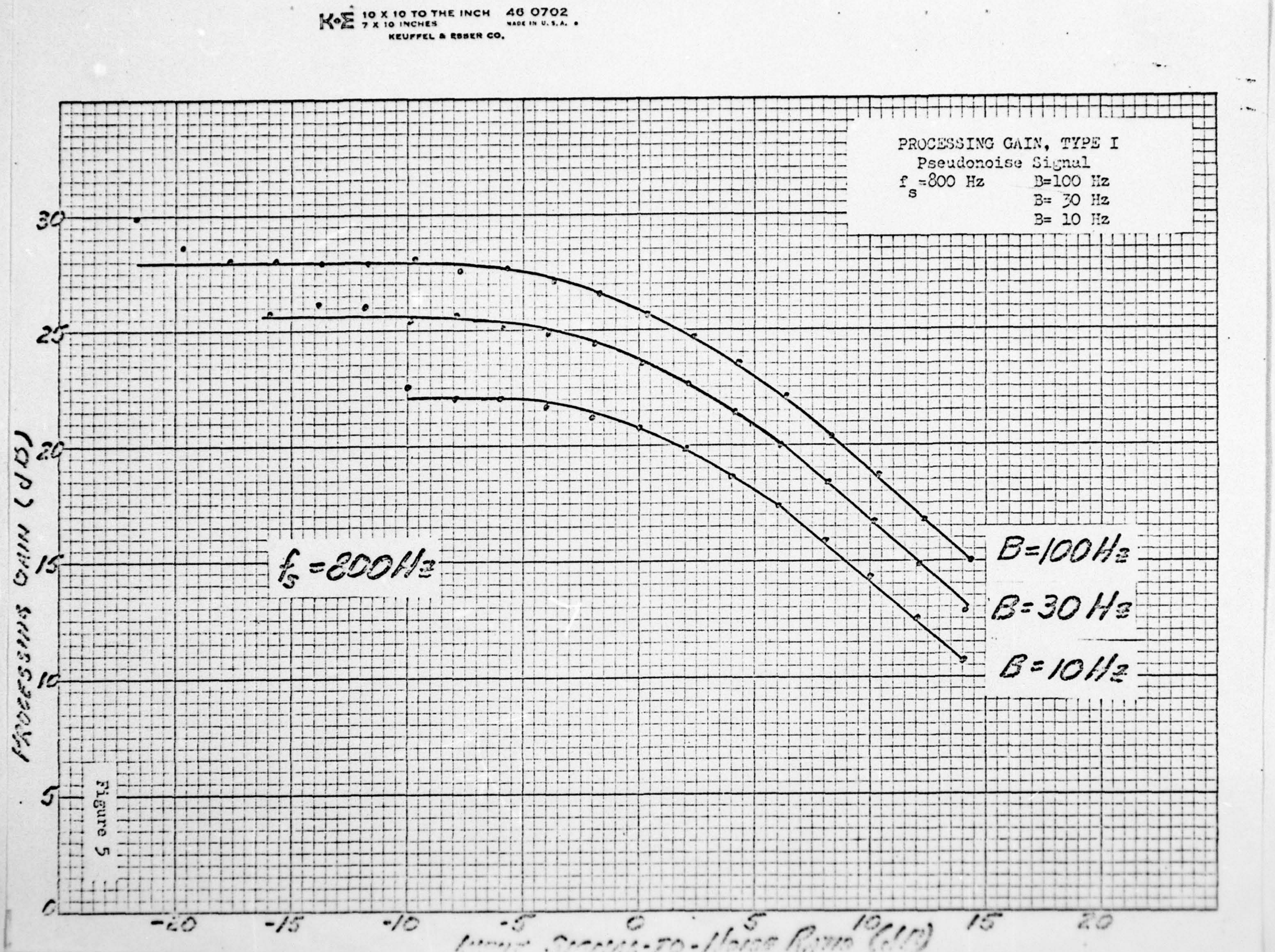

K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPE I
Pseudonoise Signal
fs=800 Hz
B=100 Hz
B= 30 Hz
B= 10 Hz
fs=800 Hz
B=100 Hz
B=30 Hz
B=10 Hz
PROCESSING GAIN (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 5

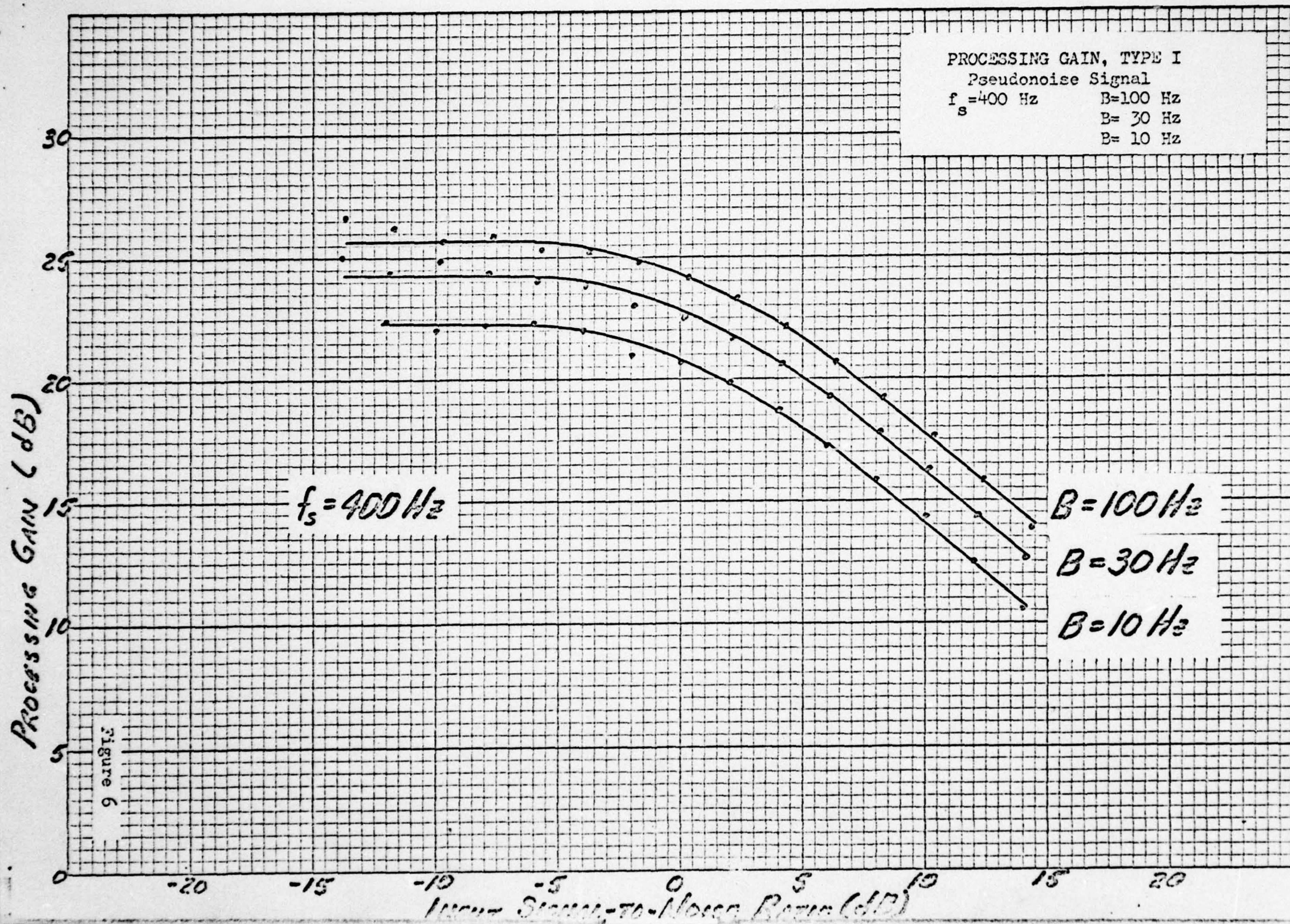

PROCESSING GAIN, TYPE I
Pseudonoise Signal
f_s=400 Hz
B=100 Hz
B= 30 Hz
B= 10 Hz
f_s=400 Hz
B=100 Hz
B=30 Hz
B=10 Hz
Processing Gain (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 6

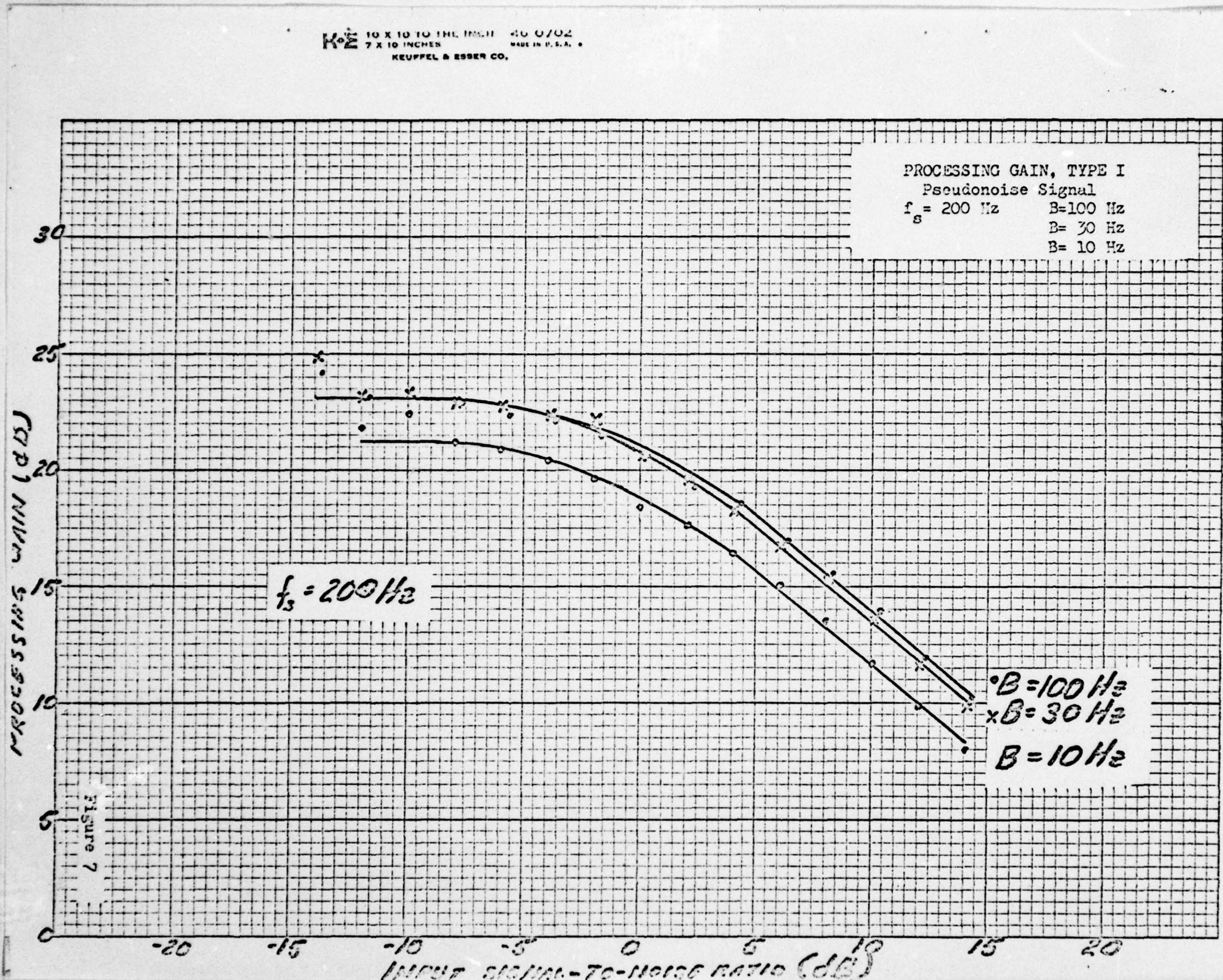

K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPE I
Pseudonoise Signal
f_s = 200 Hz B=100 Hz
B= 30 Hz
B= 10 Hz
f_s = 200 Hz
•B = 100 Hz
×B = 30 Hz
B = 10 Hz
PROCESSING GAIN (dB)
INPUT SIGNAL-TO-NOISE RATIO (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 7

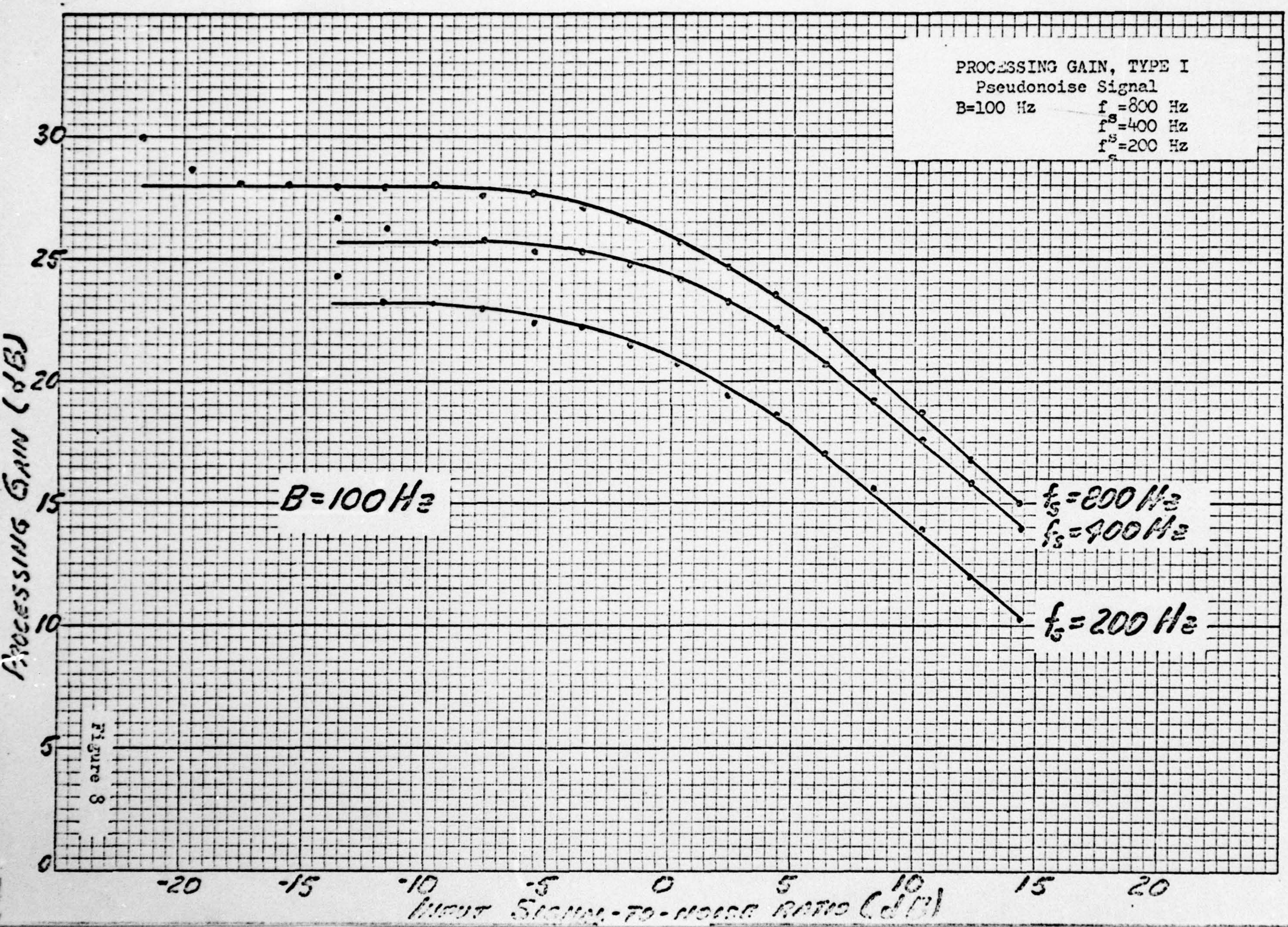
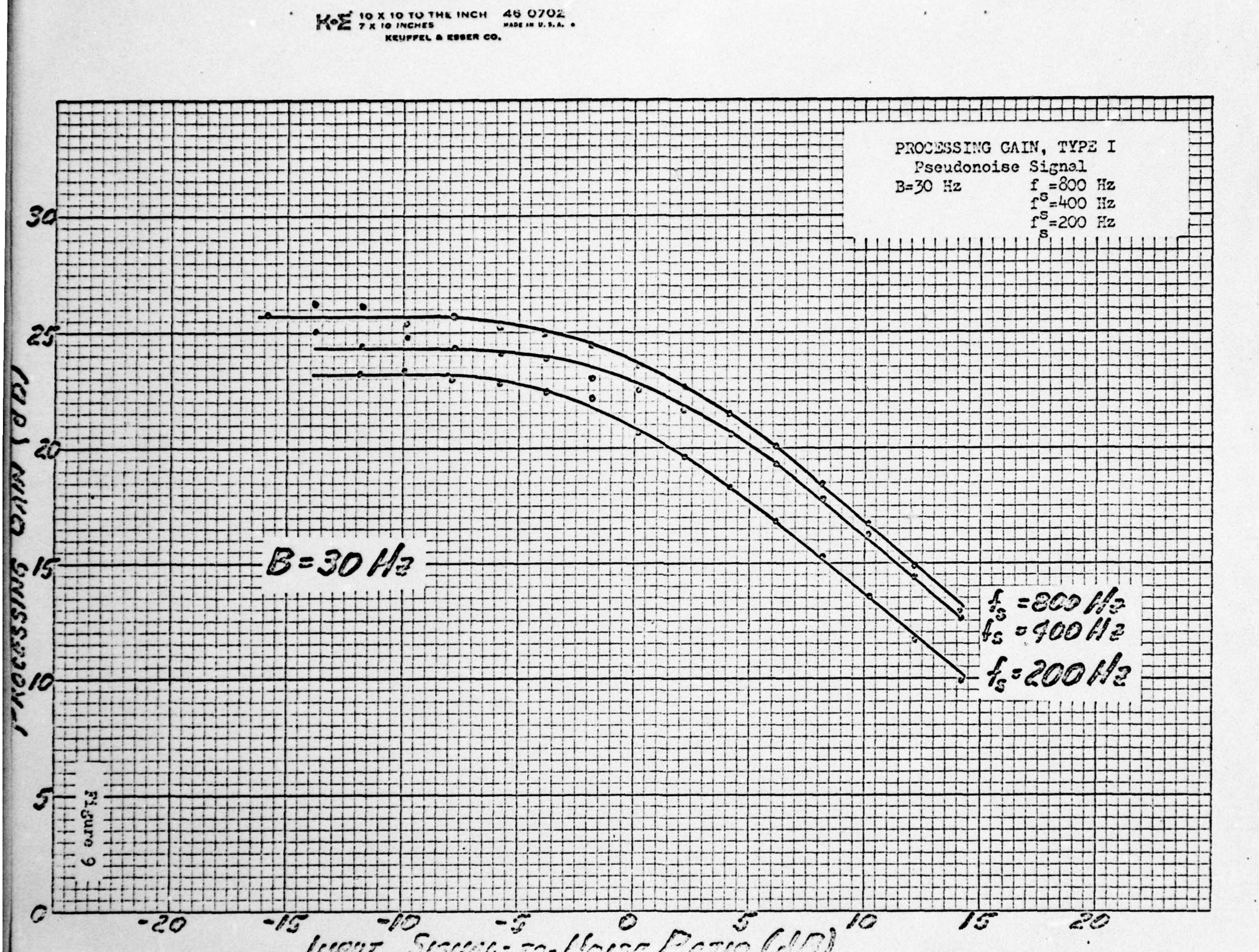

PROCESSING GAIN, TYPE I
Pseudonoise Signal
B=100 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B=100 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
PROCESSING GAIN (dB)
INPUT SIGNAL-TO-NOISE RATIO (dB)

Figure 8



K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPE I
Pseudonoise Signal
B=30 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B=30 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
Processing Gain (dB)
Input Signal-to-Noise Ratio (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 9

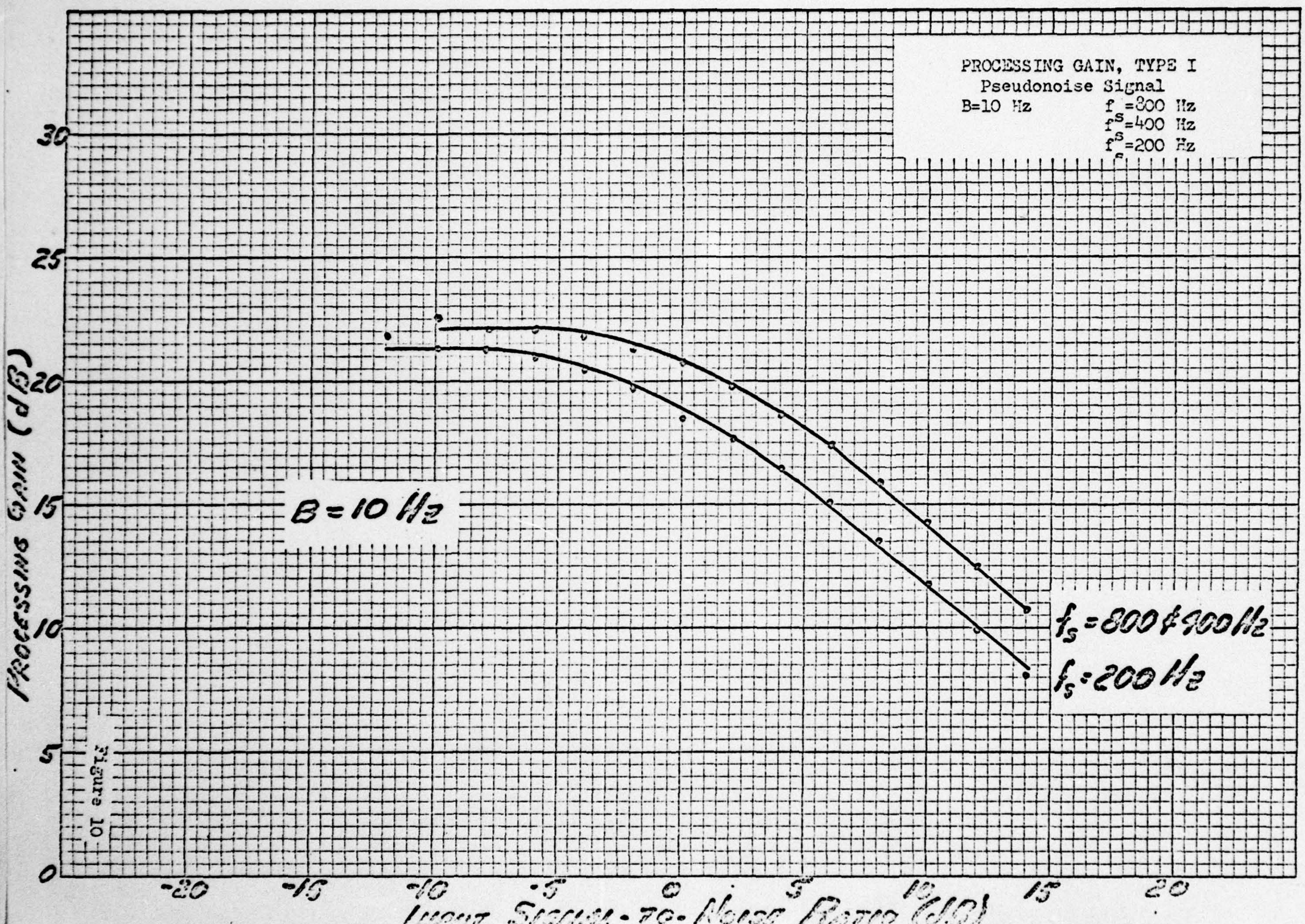

PROCESSING GAIN, TYPE I
Pseudonoise Signal
B=10 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B = 10 Hz
f_s = 800 & 400 Hz
f_s = 200 Hz
Processing Gain (dB)
Input Signal-to-Noise Ratio (dB)
0
5
10
15
20
25
30
-20
-15
-10
-5
0
5
10
15
20

Figure 10

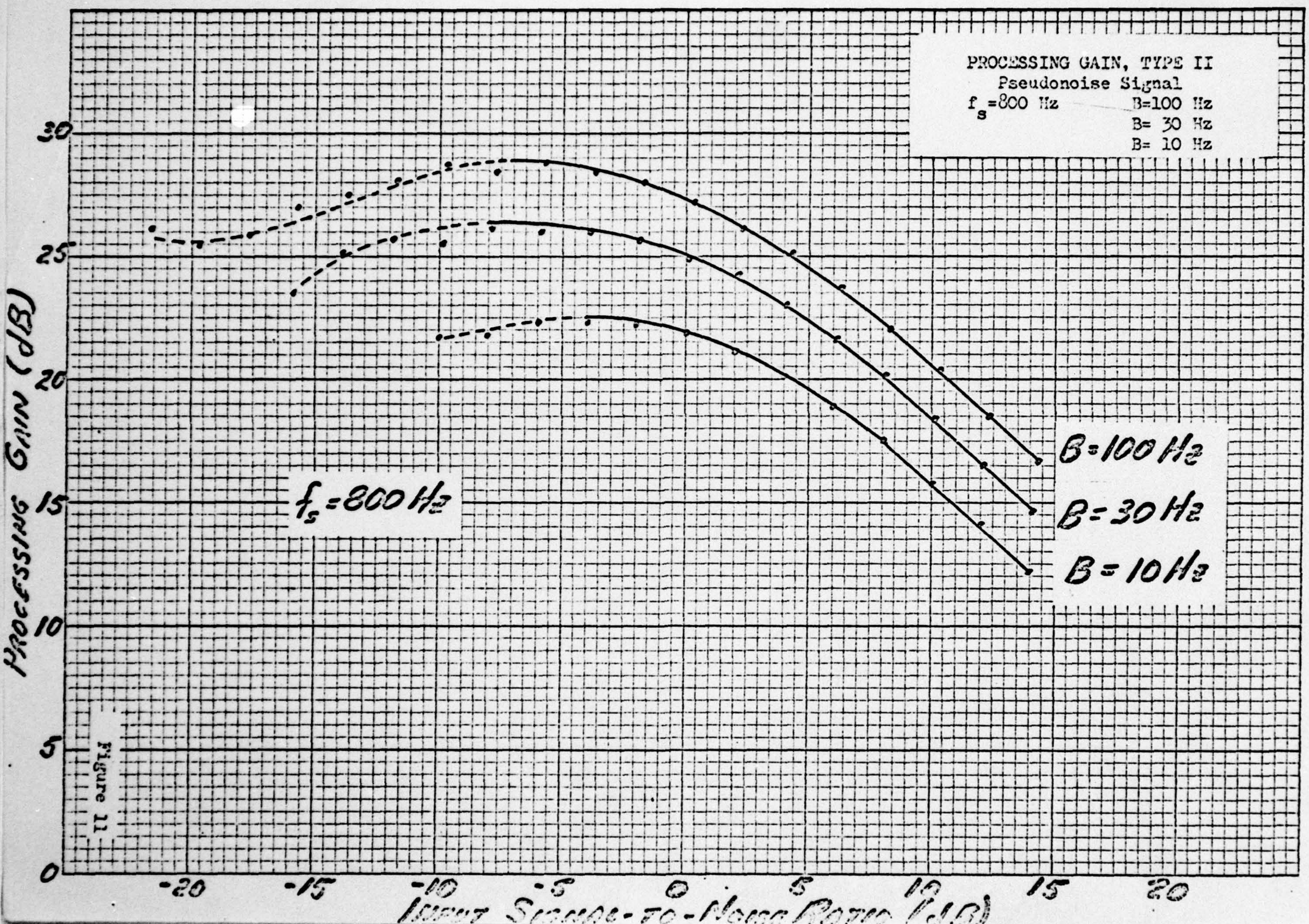

PROCESSING GAIN, TYPE II
Pseudonoise Signal
f_s=800 Hz
B=100 Hz
B= 30 Hz
B= 10 Hz
B=100 Hz
B=30 Hz
B=10 Hz
f_s=800 Hz
PROCESSING GAIN (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
INPUT SIGNAL-TO-NOISE RATIO (dB)

Figure 11

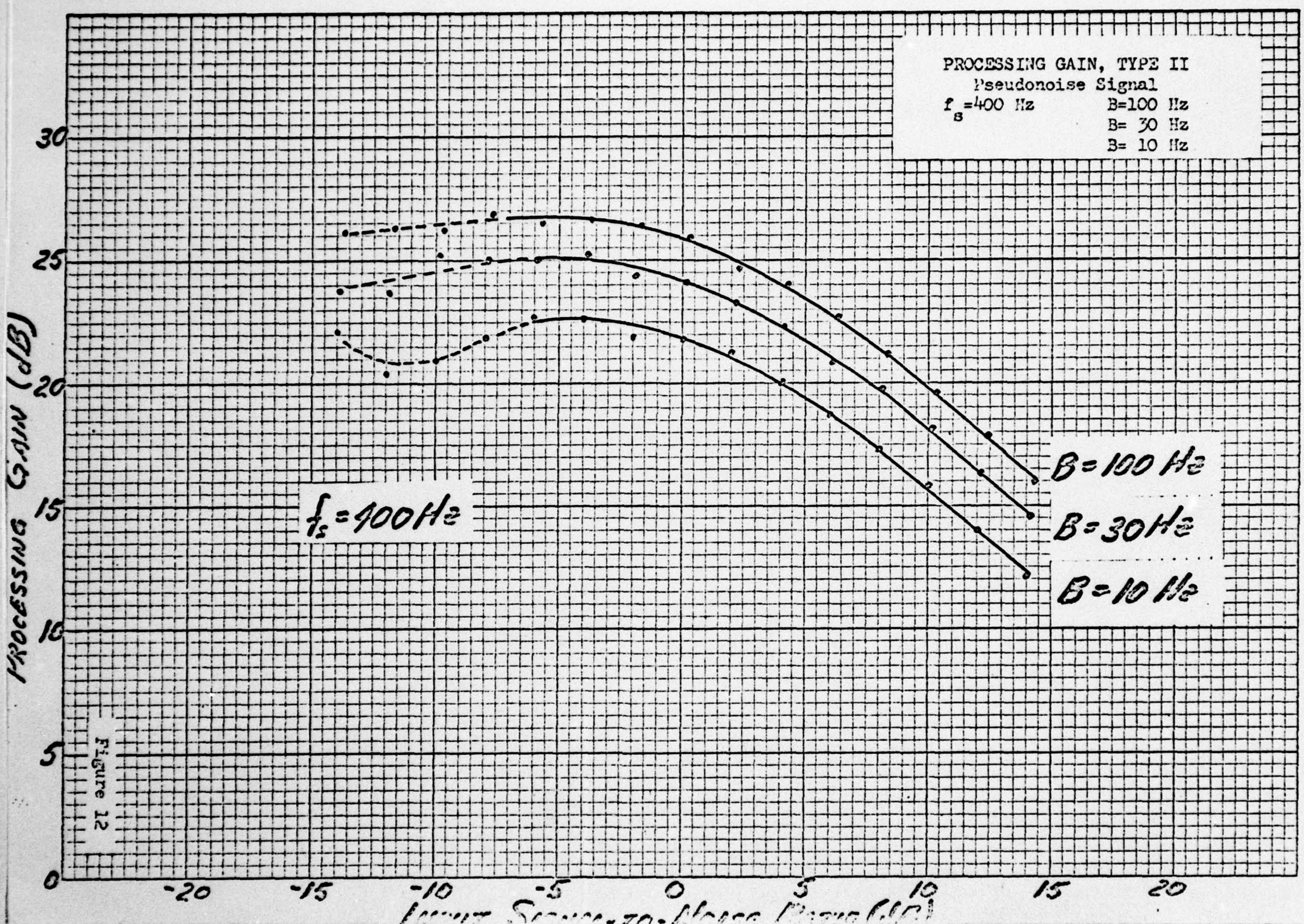
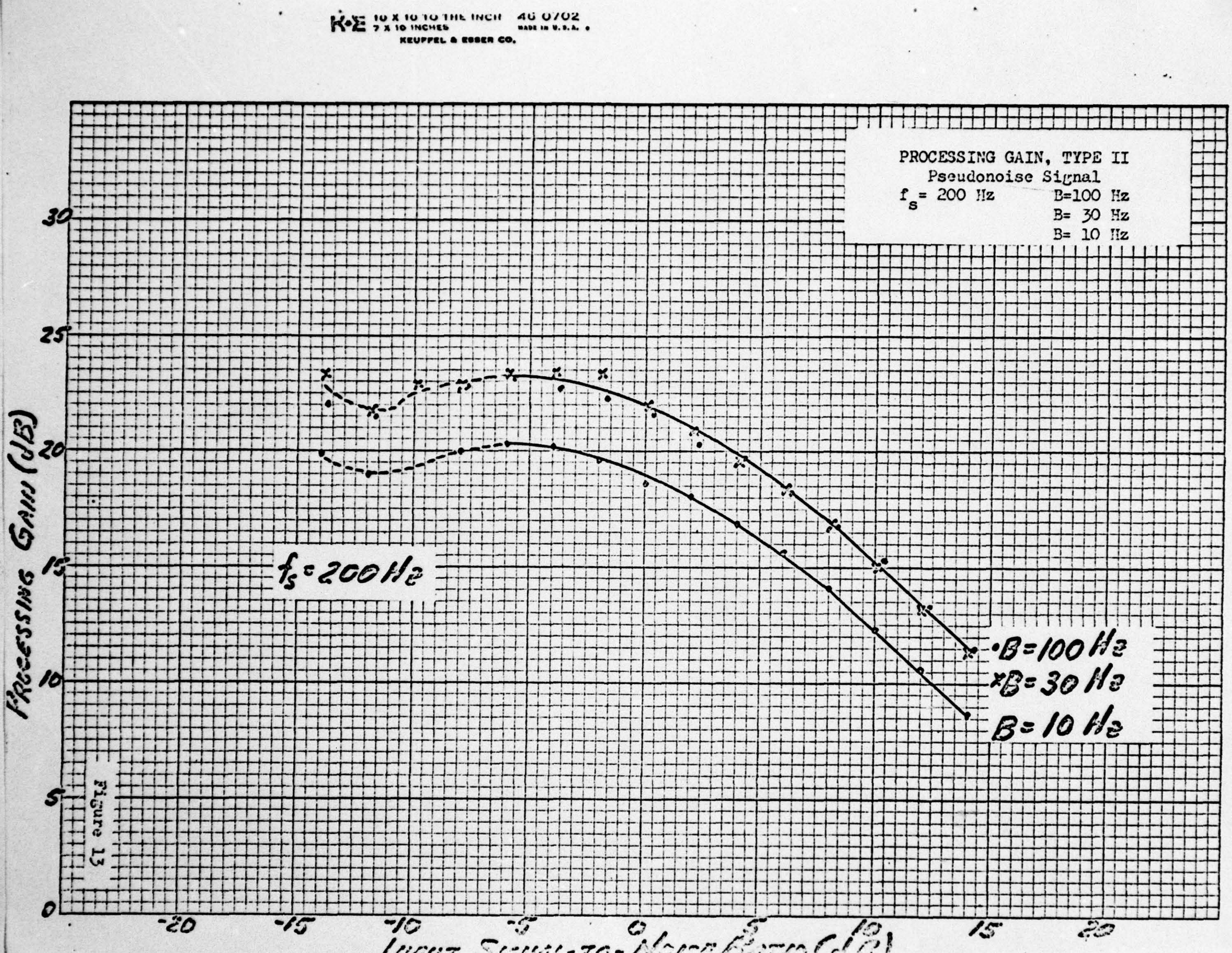

PROCESSING GAIN, TYPE II
Pseudonoise Signal
f_s=400 Hz
B=100 Hz
B= 30 Hz
B= 10 Hz
f_s=400Hz
B=100 Hz
B=30Hz
B=10 Hz
PROCESSING GAIN (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 12


K•E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPE II
Pseudonoise Signal
f_s = 200 Hz
B=100 Hz
B= 30 Hz
B= 10 Hz
f_s = 200 Hz
•B=100 Hz
×B=30 Hz
B=10 Hz
PROCESSING GAIN (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20
Figure 13

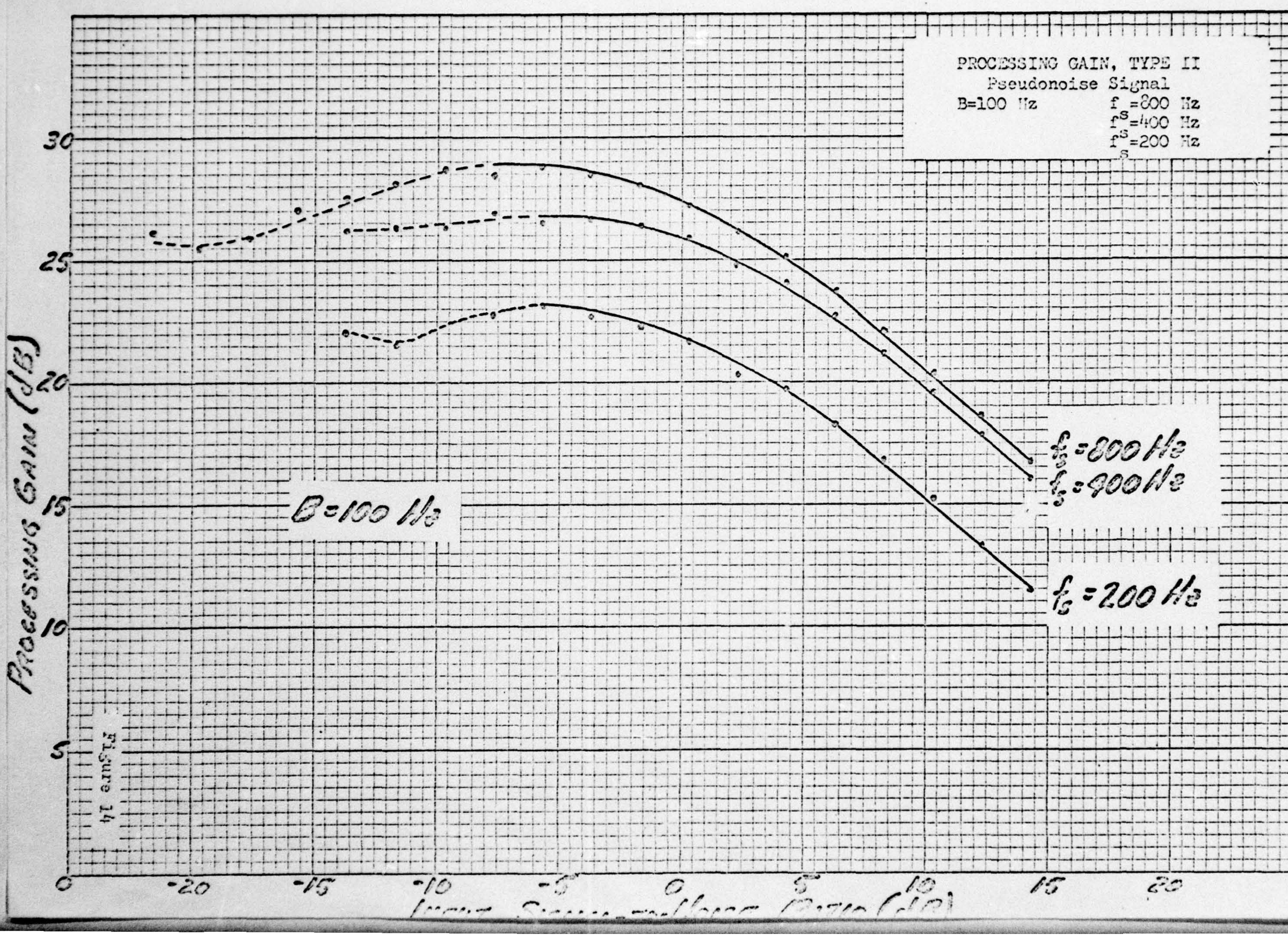

PROCESSING GAIN, TYPE II
Pseudonoise Signal
B=100 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B=100 Hz
Processing Gain (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 14

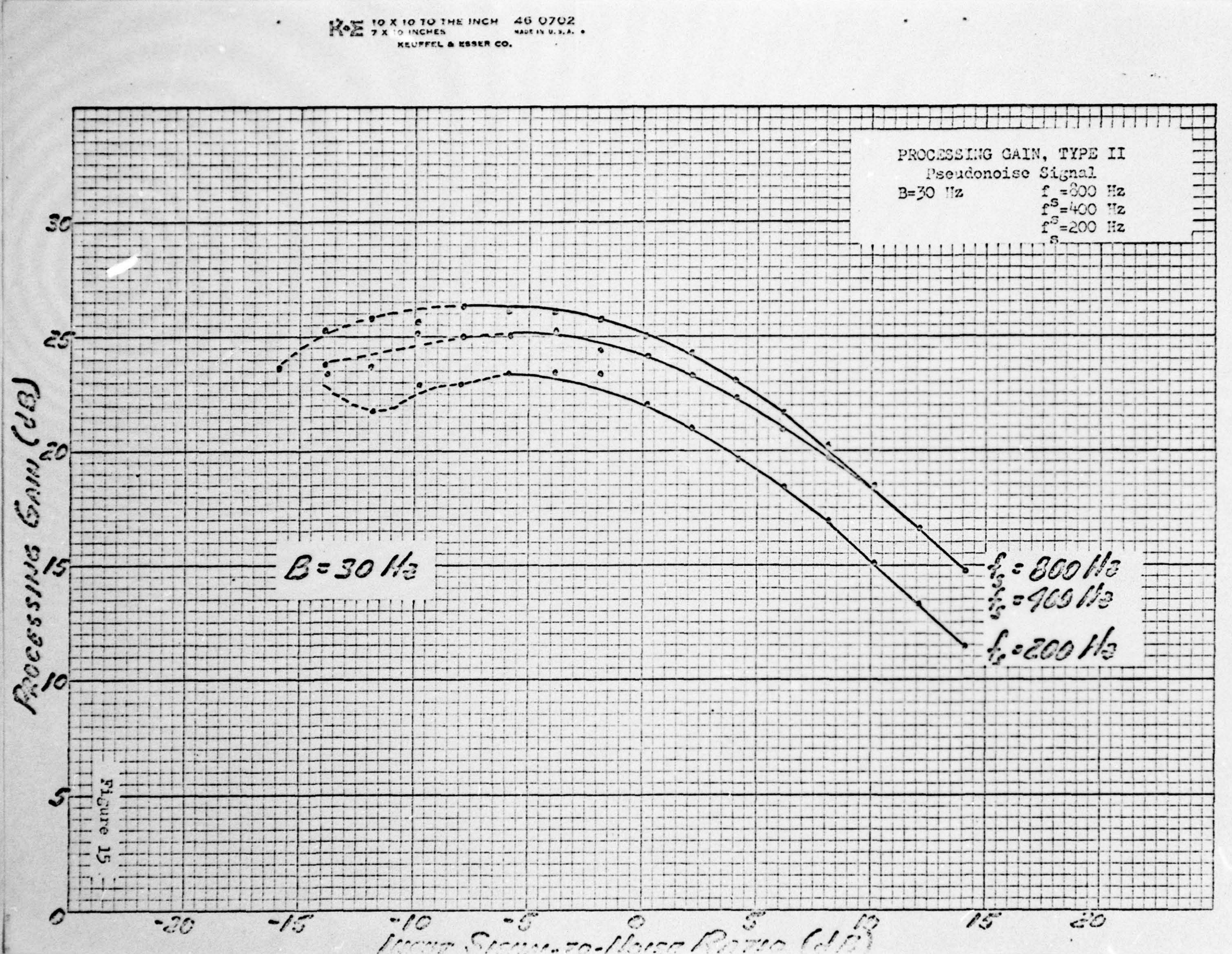

K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPE II
Pseudonoise Signal
B=30 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B = 30 Hz
f_s = 800 Hz
f_s = 400 Hz
f_s = 200 Hz
Processing Gain (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 15

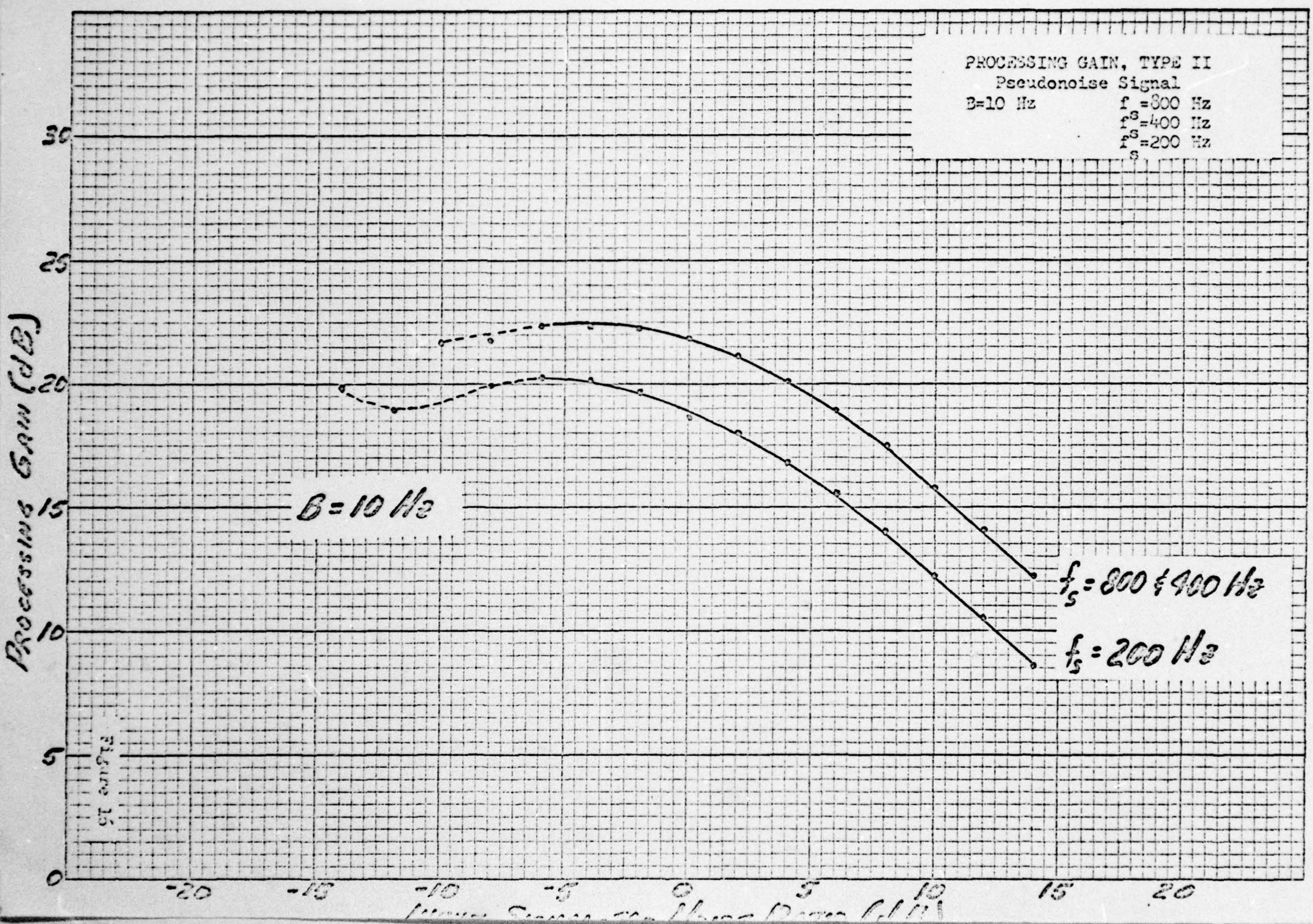

PROCESSING GAIN, TYPE II
Pseudonoise Signal
B=10 Hz
f_s=800 Hz
f_s=400 Hz
f_s=200 Hz
B = 10 Hz
f_s = 800 & 400 Hz
f_s = 200 Hz
Processing Gain (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 15

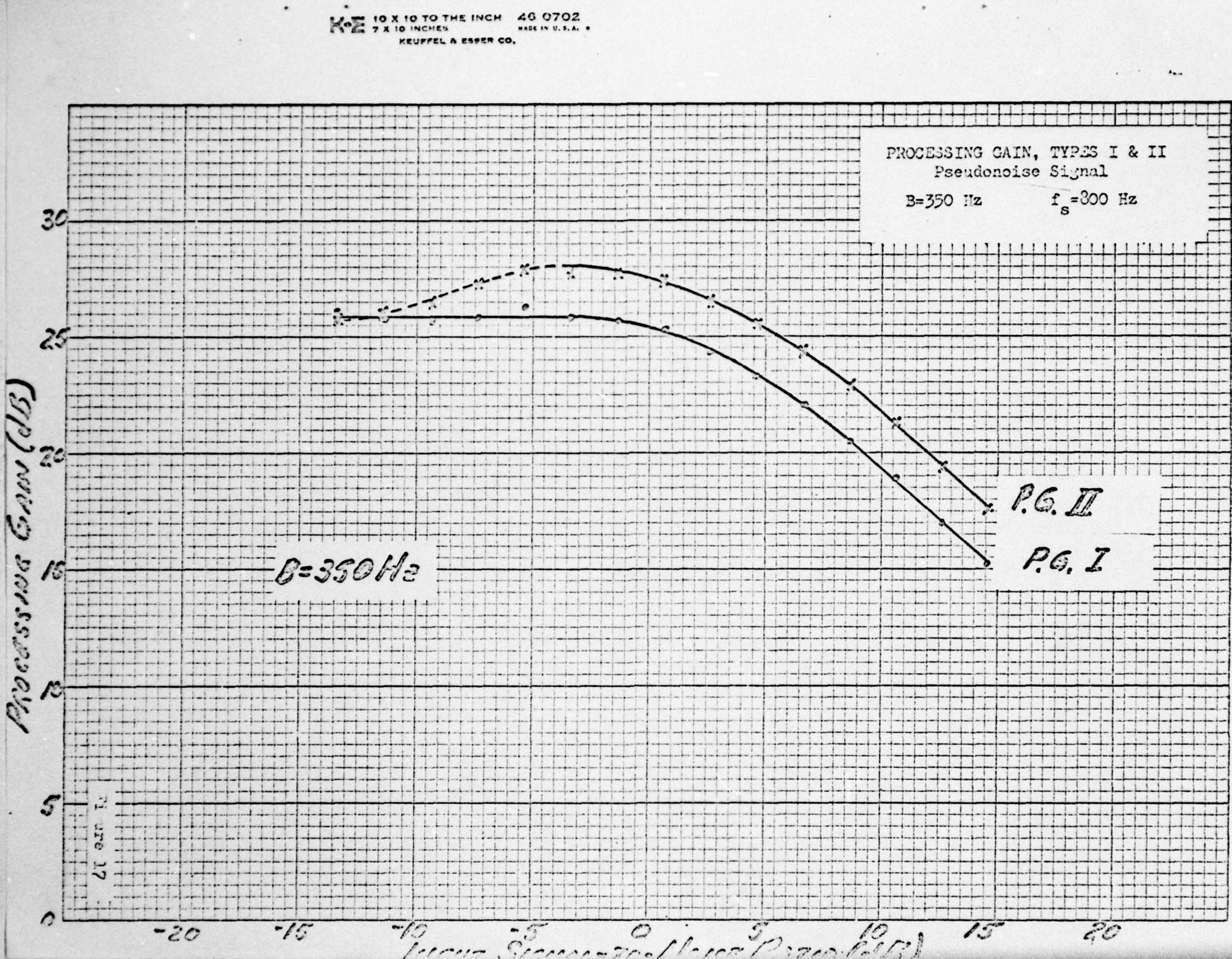

K•E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.
PROCESSING GAIN, TYPES I & II
Pseudonoise Signal
B=350 Hz
f_s=800 Hz
P.G. II
P.G. I
B=350 Hz
Processing Gain (dB)
30
25
20
15
10
5
0
-20
-15
-10
-5
0
5
10
15
20

Figure 17

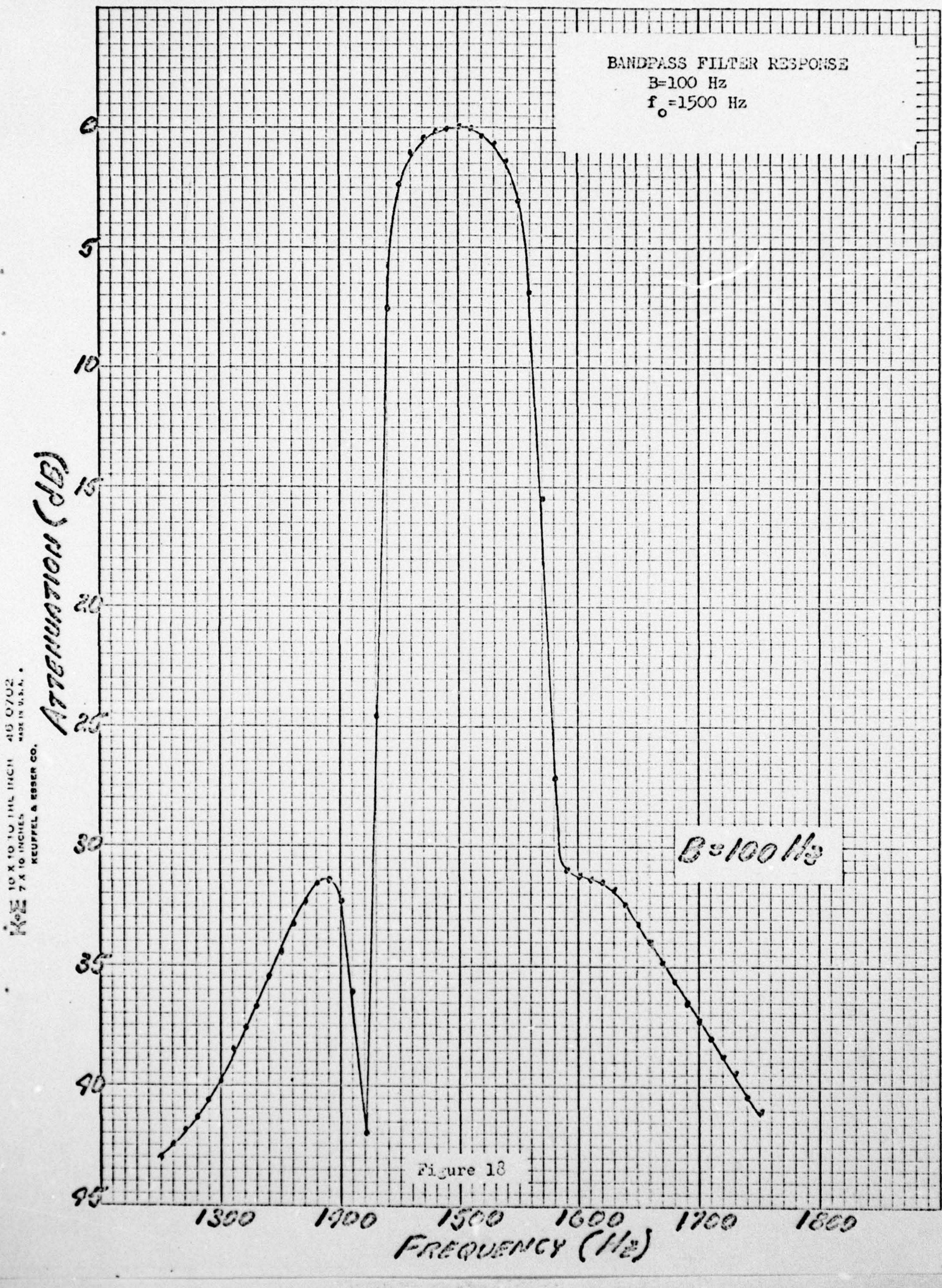

BANDPASS FILTER RESPONSE
B=100 Hz
f_o=1500 Hz
B=100 Hz
0
5
10
15
20
25
30
35
40
45
1300
1400
1500
1600
1700
1800
FREQUENCY (Hz)
ATTENUATION (dB)
K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

Figure 18

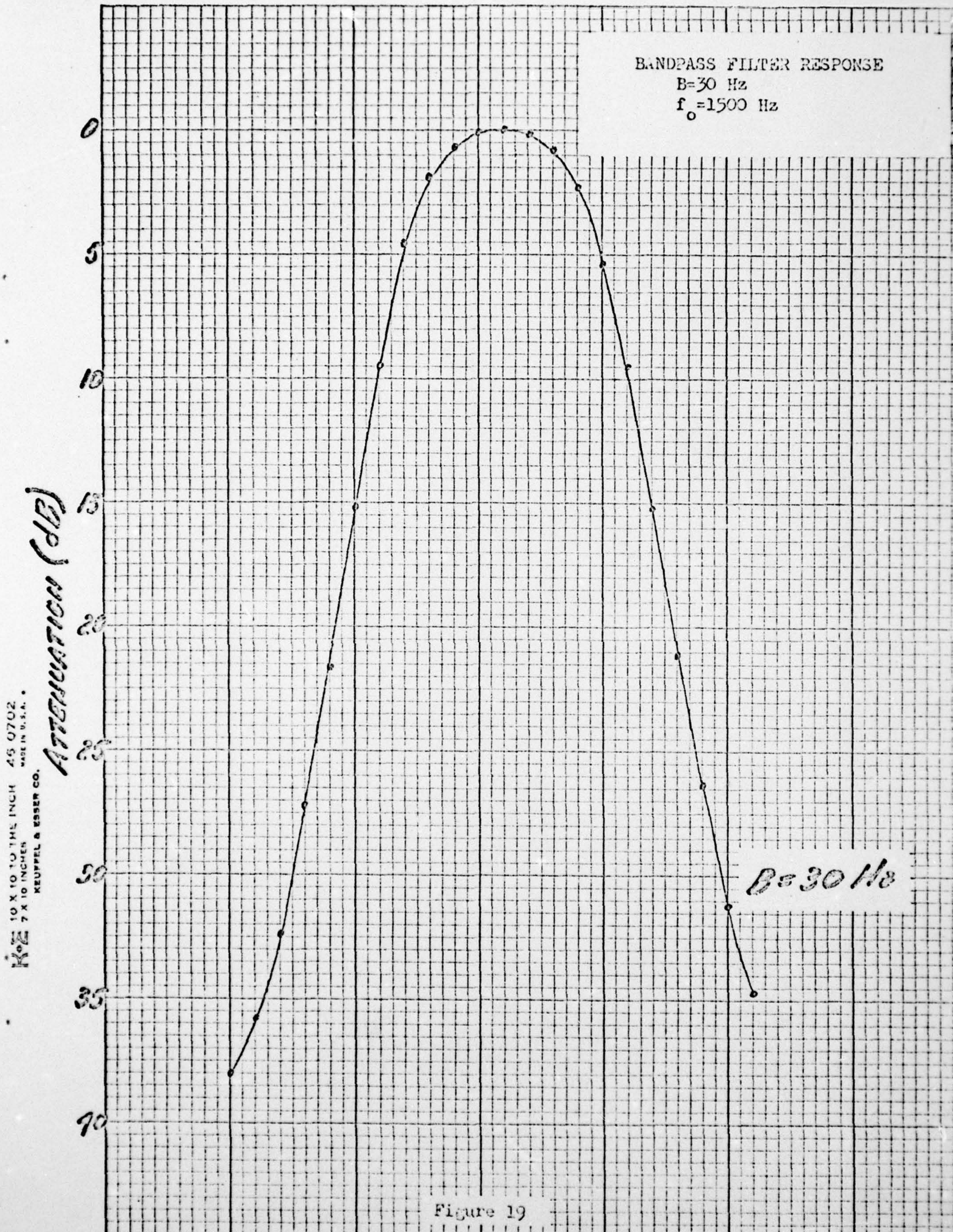
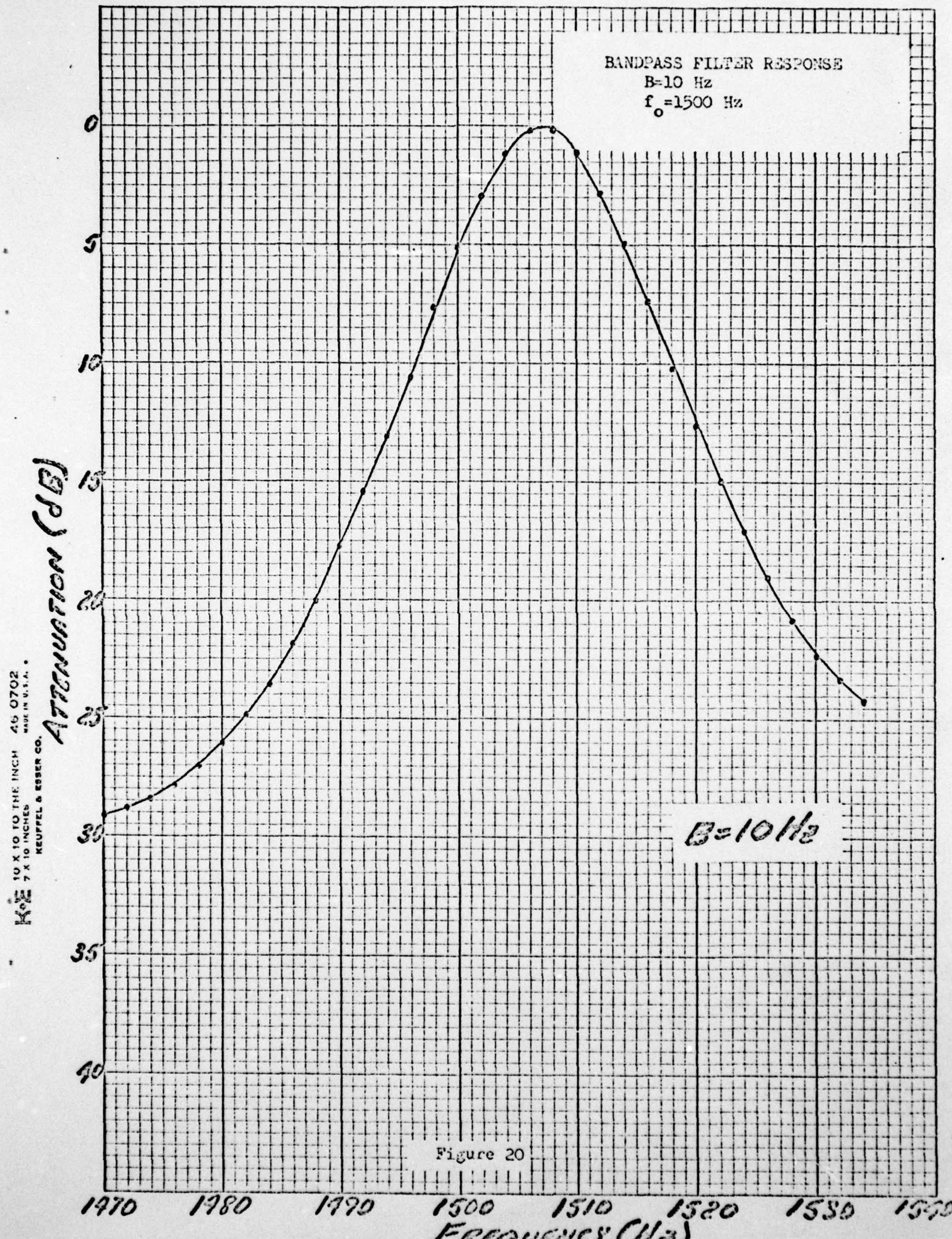

BANDPASS FILTER RESPONSE
B=30 Hz
f_o=1500 Hz
B=30 Hz
ATTENUATION (dB)
0
5
10
15
20
25
30
35
40
1450
1475
1500
1525
1550
1575
FREQUENCY (Hz)
K&E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

Figure 19



BANDPASS FILTER RESPONSE
B=10 Hz
f_o=1500 Hz
B=10Hz
ATTENUATION (dB)
0
5
10
15
20
25
30
35
40
1470
1480
1490
1500
1510
1520
1530
1540
FREQUENCY (Hz)
10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

Figure 20

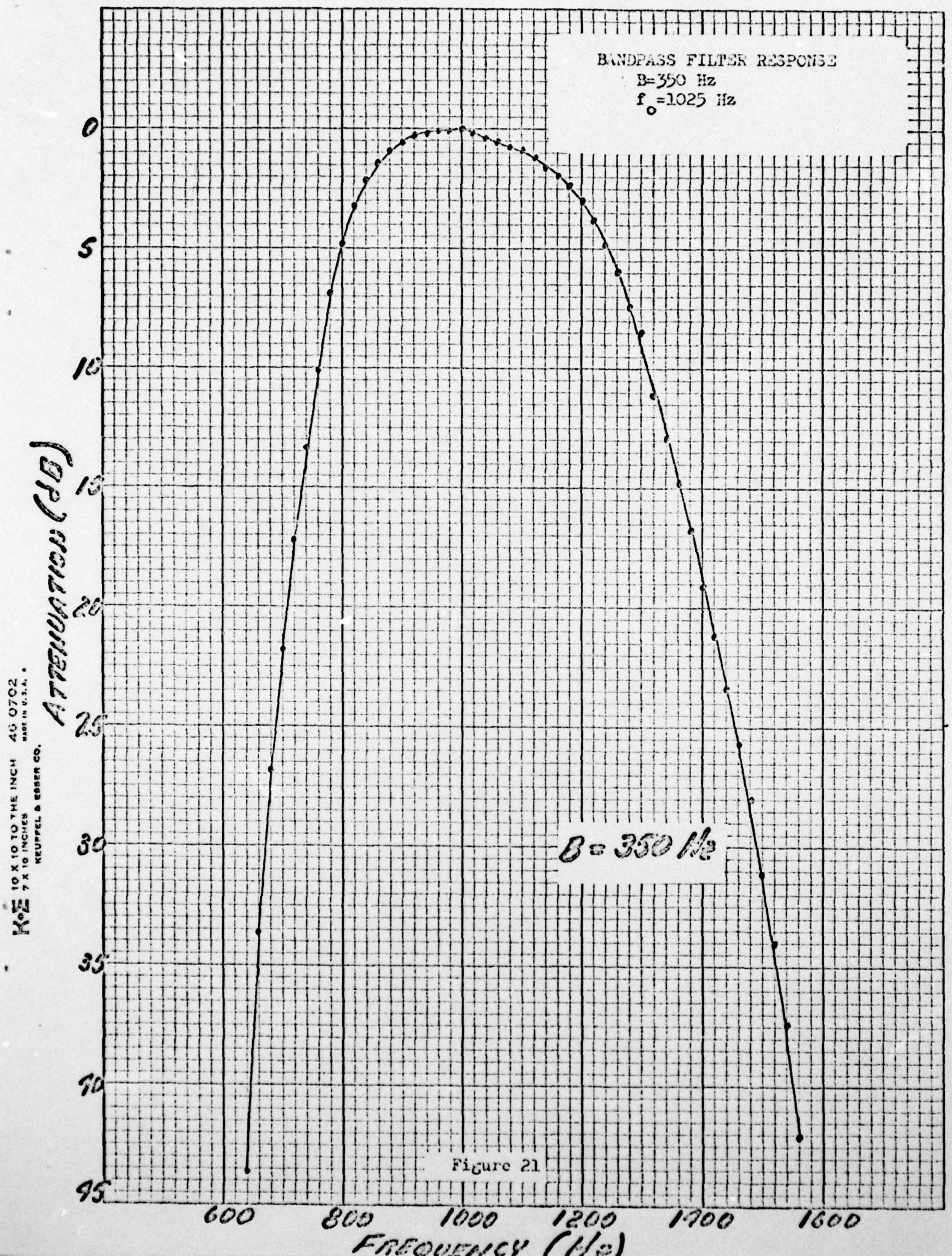

BANDPASS FILTER RESPONSE
B=350 Hz
f_o=1025 Hz
B = 350 Hz
ATTENUATION (dB)
FREQUENCY (Hz)
0
5
10
15
20
25
30
35
40
45
600
800
1000
1200
1400
1600
K+E 10 X 10 TO THE INCH 46 0702
7 X 10 INCHES MADE IN U.S.A.
KEUFFEL & ESSER CO.

Figure 21

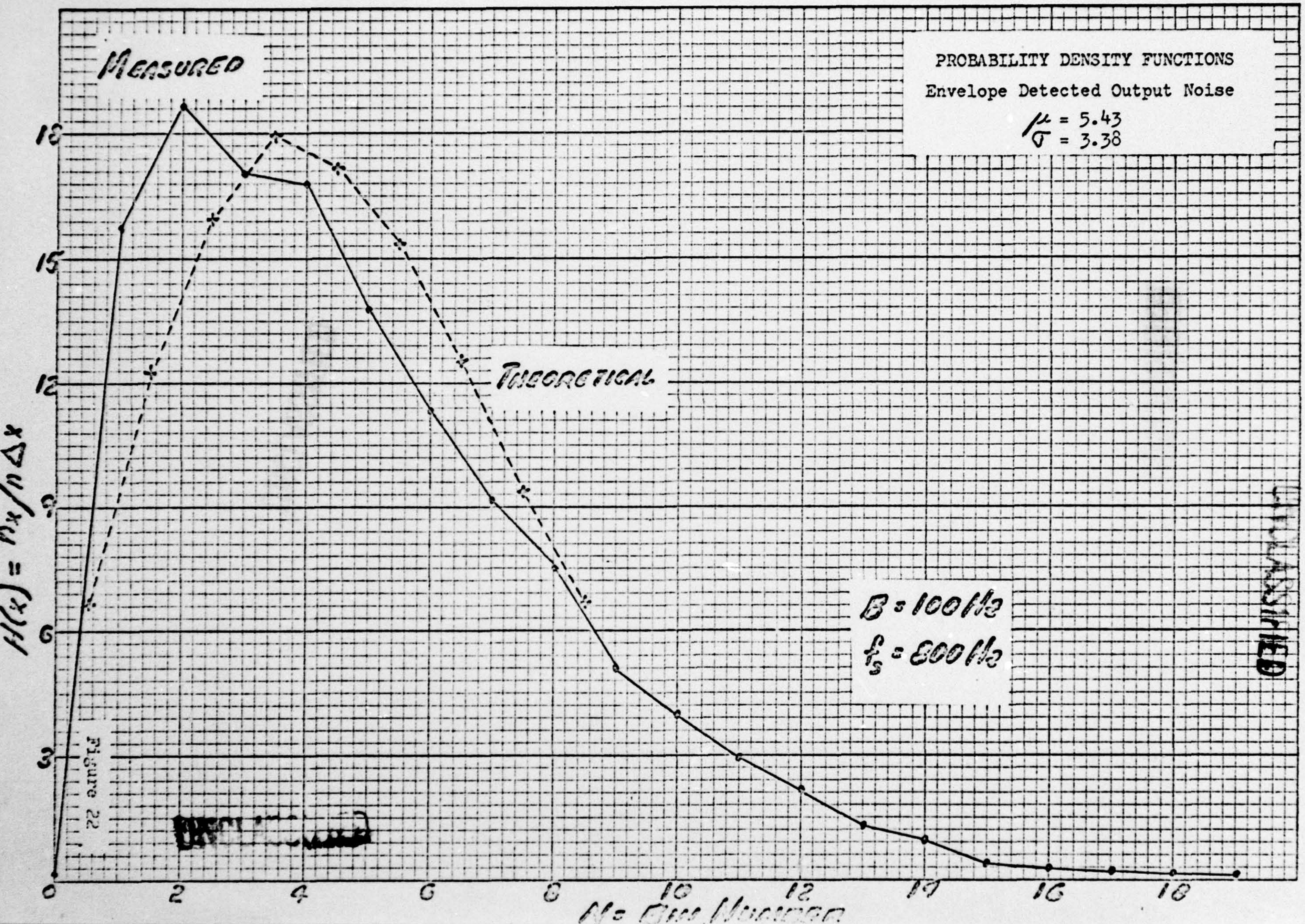

PROBABILITY DENSITY FUNCTIONS
Envelope Detected Output Noise
μ = 5.43
σ = 3.38
MEASURED
THEORETICAL
B = 100 Hz
f_s = 800 Hz
H(x) = $n_x/n\Delta x$
18
15
12
9
6
3
0
2
4
6
8
10
12
14
16
18

Figure 22